



Micro-/nanostructure-enabled optical-field engineering: Enhancing rare-earth upconversion luminescence and applications

Yanan Ji, Tingting Zhang, Wen Xu*, Bin Dong*

Key Laboratory of New Energy and Rare Earth Resource Utilization of State Ethnic Affairs Commission, Key Laboratory of Photosensitive Materials & Devices of Liaoning Province, School of Physics and Materials Engineering, Dalian Minzu University, 18 Liaohe West Road, Dalian 116600, Liaoning, China.

***Correspondence to:** Wen Xu, Key Laboratory of New Energy and Rare Earth Resource Utilization of State Ethnic Affairs Commission, Key Laboratory of Photosensitive Materials & Devices of Liaoning Province, School of Physics and Materials Engineering, Dalian Minzu University, 18 Liaohe West Road, Dalian 116600, Liaoning, China. E-mail: xuwen@dlmu.edu.cn

Bin Dong, Key Laboratory of New Energy and Rare Earth Resource Utilization of State Ethnic Affairs Commission, Key Laboratory of Photosensitive Materials & Devices of Liaoning Province, School of Physics and Materials Engineering, Dalian Minzu University, 18 Liaohe West Road, Dalian 116600, Liaoning, China. E-mail: dong@dlmu.edu.cn

Received: December 31, 2025 **Accepted:** March 10, 2026 **Published:** March 16, 2026

Cite this article: Ji Y, Zhang T, Xu W, Dong B. Micro-/nanostructure-enabled optical-field engineering: Enhancing rare-earth upconversion luminescence and applications. *Light Manip Appl.* 2026;1:202507. <https://doi.org/10.70401/lma.2026.0006>

Abstract

Rare-earth-doped upconversion nanocrystals (UCNCs), with unique anti-Stokes emission, have been extensively explored, while their performances are hindered by the restriction of parity-forbidden $4f-4f$ transitions, making their emission difficult to control and resulting in low quantum yields. Current research primarily relies on modifying dopant types and concentrations, matrix composition, particle size, core-shell structures, and surface functional groups, to tune the absorption and emission transitions of $4f$ electrons. While these methods can effectively adjust emission spectra, reduce defects, and enhance luminescence efficiency, they cannot fundamentally regulate the $4f$ electron transition process, especially with respect to studying the intrinsic luminescence kinetics of rare earth ions. Therefore, a fundamental understanding of the transition behavior of $4f$ electrons and the ability to intrinsically control their absorption and emission processes are crucial. By manipulating the local optical field around UCNCs, micro-nano structures offer a powerful means to control their upconversion luminescence, making them an important tool for developing efficient optoelectronic devices for display, lighting, and conversion applications. In this review, we comprehensively expound on the optical engineering for UC luminescence control through micro/nano-optical structures. By utilizing structures such as plasmonic antennas, dielectric superstructures, high Q microcavities, and programmable wavefront shapers, precise control over the interaction between light and matter is achieved at multiple spatial scales. Moreover, we systematically analyze how such structures enhance local excitation fields, amplify spontaneous emission, and direct photon extraction, thereby transcending the inherent limitations of rare-earth emitters. By bridging advances in materials chemistry with nanophotonics design principles, this approach unlocks unprecedented control over UC efficiency, spectral purity, and polarization properties.

Keywords: Upconversion luminescence, localized optical field modulation, dielectric metasurfaces, optical microcavity, wavefront control

1. Introduction

Rare-earth (RE)-doped upconversion nanocrystals (UCNCs) constitute a unique class of luminescent materials capable of converting multiple low-energy near-infrared (NIR) photons into higher-energy ultraviolet (UV) or visible (Vis) emissions, underpinned by the unique electronic structure of lanthanide ions^[1,2]. A defining bottleneck of RE upconversion lies in the parity-forbidden nature of $4f-4f$ electronic transitions, a constraint dictated by quantum mechanical selection rules. The $4f$ orbitals of lanthanide ions are spatially shielded by outer $5s^25p^6$ orbitals, resulting in minimal overlap with the electromagnetic field of incident light and extremely weak electric dipole transition probabilities^[3,4]. This intrinsic limitation directly manifests in two critical performance drawbacks: inherently low photoluminescence quantum yields (PLQYs, initially $< 0.1\%$ under moderate irradiance) due to dominant non-radiative decay pathways (e.g., phonon-assisted relaxation, surface defect quenching), and poor controllability over emission properties (spectral linewidth, polarization, directionality), which collectively hinder UCNC applications in low-power, high-precision



scenarios^[5,6].

The root cause of these challenges stems from the need for a fundamental understanding of 4f electron transition behavior to regulate absorption and emission processes. Lanthanide 4f electrons exhibit unique radial distribution and spin-orbit coupling effects, with transitions primarily mediated by weak electric dipole and magnetic dipole interactions^[7,8]. The shielding effect of outer orbitals not only reduces transition probabilities but also leads to narrow absorption linewidths (~1–10 nm) and sensitivity to local crystal fields. Thus, effectively regulating 4f electron transitions requires precise control over the interaction between electrons and the surrounding electromagnetic environment^[9,10].

Manipulating the local optical field emerges as a rational strategy to regulate 4f electron transition processes, as it bypasses the intrinsic parity-forbidden limitation by enhancing the effective electromagnetic field-matter coupling. Specific mechanisms to address the aforementioned challenges include: (1) Concentrating incident light via plasmonic hotspots or dielectric resonant modes to compensate for small 4f-4f absorption cross-sections (~10⁻²⁰ cm²); (2) Modulating the radiative decay rate of 4f electrons via high-Q resonators to suppress non-radiative decay and improve PLQYs; (3) Tailoring the local density of optical states (LDOS) via photonic structures to enhance transition probabilities of 4f electrons; (4) Using wavefront shaping or resonant filtering to align broad excitation sources with narrow 4f absorption lines, boosting photon harvesting efficiency. These mechanisms collectively enable active regulation of 4f electron transitions, complementing conventional materials engineering^[11,12]. Early studies focused on compositional and morphological engineering of the NCs themselves, like optimizing dopant ratios, core-shell architectures, and phonon environments to suppress non-radiative decay^[13-15]. These efforts raised the absolute quantum yields from < 0.1% to > 10% under modest irradiance, yet the absorption cross-sections of parity-forbidden 4f-4f transitions remain intrinsically small (~10⁻²⁰ cm²), and the broad spectral bandwidths of conventional excitation sources still overlap poorly with the narrow linewidths of lanthanide ions. Consequently, most incident photons remain unabsorbed^[16-18].

The past decade has witnessed a paradigm shift: instead of treating UCNCs as an isolated emitter, researchers now engineer the surrounding electromagnetic environment to concentrate, spectrally filter, and dynamically re-route the excitation light. This has been enabled by parallel revolutions in nanophotonics, spanning plasmonic antennas, dielectric metasurfaces, high-Q whispering-gallery resonators, and adaptive wavefront-shaping devices, that operate at precisely the wavelengths where rare-earth sensitizers absorb^[19-23]. The convergence of these fields has yielded orders-of-magnitude enhancements in effective absorption, single-particle brightness, and spectral selectivity, while simultaneously relaxing the stringent requirements on excitation power and thermal load.

In this review, we examine how light-field engineering strategies complement, rather than compete with, conventional materials optimizations (Scheme 1). Section 2 dissects the design principles for manipulating optical fields at three complementary length scales: local-field enhancement (plasmonic hotspots and photonic crystal band-edge modes), resonant-mode management (dielectric metasurfaces and optical microcavities), and macroscopic wavefront shaping (microlens arrays and liquid-crystal modulators). Each subsection links theoretical metrics (e.g., Purcell factor, LDOS, and external quantum yield) to experimentally observed gains in UC efficiency and spectral tunability, elucidating the underlying physical links between optical field manipulation and 4f electron transition regulation. Building upon this enhanced control over light-matter interactions, Section 3 reviews the transformative applications enabled by engineered upconversion luminescence (UCL), where rational light-field design has broken performance bottlenecks in key areas including high-sensitivity photodetectors (PDs) and solar cells. By uniting the traditionally separate communities of materials chemistry and nanophotonics, engineered light fields are poised to redefine the efficiency ceiling and application space of rare-earth upconversion.

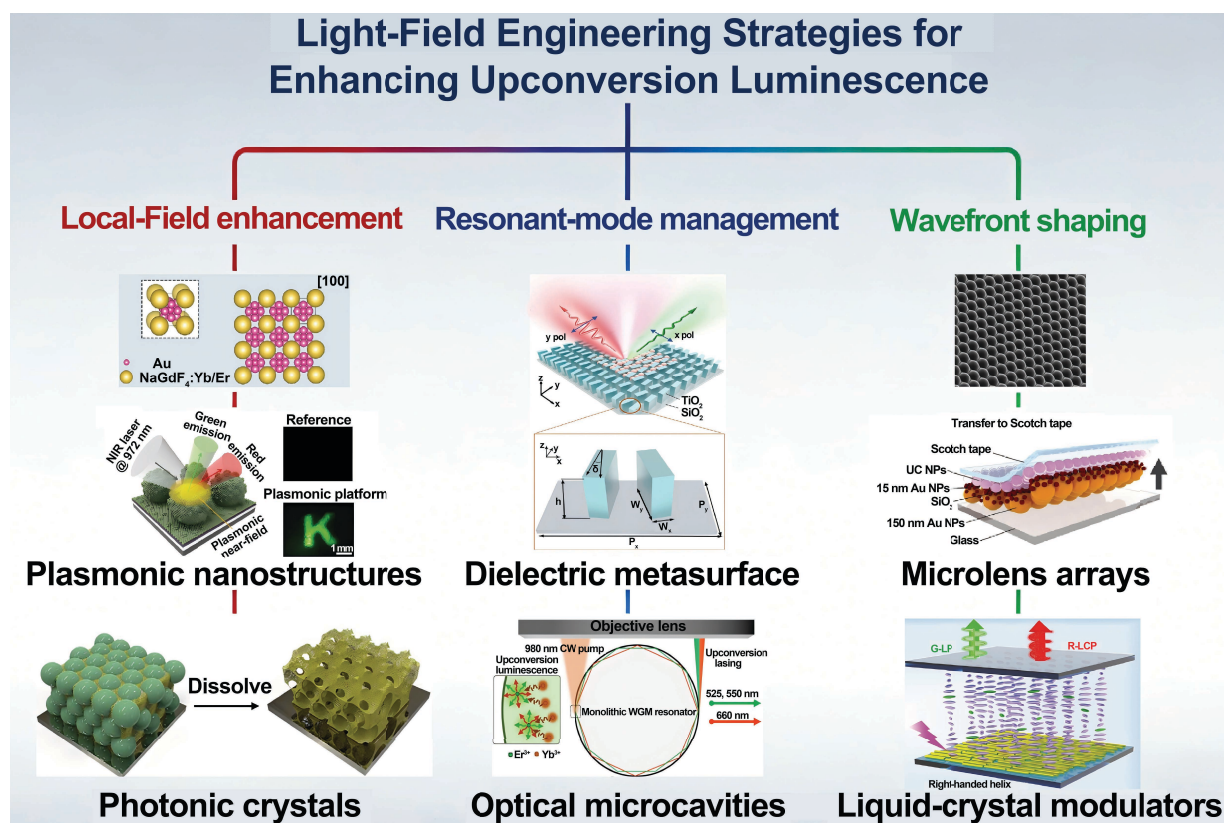
2. Light-Field Engineering Strategies

2.1 Local-field enhancement

2.1.1 Plasmonic nanostructures

In 1985, Malta *et al.* reported the fluorescence properties of borosilicate glass co-doped with metal nanoparticles and Eu³⁺ ions, laying early groundwork for plasmon-lanthanide interactions^[32]. Subsequent research established that the localized surface plasmon resonance (LSPR) properties, and thus their efficacy in enhancing UCL, are governed by the nanostructures' size, shape, and composition. Anisotropic morphologies, in particular, enable broad spectral tuning to match narrow 4f absorption lines of specific lanthanide ions^[33]. For instance, sharp features in silver nanoprisms induce spectral shifts over 4 nm per CH₂ unit in adsorbed molecules, far exceeding the sensitivity of periodic gold film arrays^[34-36]. A critical advancement in plasmon-enhanced UCL has been the quantitative mapping of the distance-dependent interplay between enhancement and quenching. A representative study employed layer-by-layer polyelectrolyte spacers to precisely tune the separation between upconversion nanoparticles (UCNPs) and gold nanorods (Au NRs) antennas. A maximum 22.6-fold UCL enhancement was achieved at an optimal spacer thickness of ~8 nm, demonstrating the narrow window for near-field enhancement before non-radiative energy transfer to the metal dominates^[37]. Parallel progress in synthesis has enabled precise geometric control of hybrid nanostructures. Methods such as interfacial energy modulation in mixed solvents allow reproducible fabrication of anisotropic architectures (core-shell, eccentric, and Janus) in a single

reaction, paving the way for structures optimized for specific lanthanide emitters^[38].



Scheme 1. Schematic illustration of the main strategies for light-field modulating UCL. Republished with permission from^[24-31]. UCL: upconversion luminescence.

Systematic investigations have further detailed the size-dependent modulation of UCL. For example, Mendez-Gonzalez *et al.* showed that for Au NPs (4–66 nm), strong quenching via energy transfer peaks at a small optimal size; beyond this size, plasmonic enhancement becomes dominant, counterbalancing and eventually surpassing quenching^[39]. Ananda Das *et al.* designed the lithographically fabricated metal-insulator-metal (MIM) nanostructures, achieving over 1,000-fold UCL enhancement. The cross-section scanning electron microscopy (SEM) image of resist hole array template after the UCNPs dropcast step and angled SEM image of MIM after resist removal are shown in Figure 1a,b, respectively^[40]. Affording both scalability and excellent uniformity, this method reliably produces large-area substrates with uniform subwavelength gaps. These gaps are essential for generating confined gap-plasmon modes and the resultant intense local field enhancement, which directly improves $4f$ electron-field coupling to overcome the low oscillator strength of parity-forbidden transitions. This uniformity ensures consistent $4f$ transition modulation, a key practical advantage for device fabrication. Quan *et al.* demonstrated plasmonic modulation of UCL by constructing long-range ordered, two-dimensional (2D) binary nanoparticle superlattices (BNSLs) via self-assembly of spherical UCNPs and Au NPs (Figure 1c)^[24]. As revealed by transmission electron microscope image (Figure 1d), the BNSLs exhibit high-quality periodic organization, preferentially oriented with the [100] plane exposed on the substrate (Figure 1e). Optical characterization confirmed effective modulation of the typical UCNP emission profile within the BNSLs, resulting in a spectral shift toward the reddish output and a concomitant significant reduction in luminescence lifetime. This long-range order induces collective plasmonic modes that tailor the LDOS around UCNPs, selectively enhancing radiative decay of specific $4f$ electron levels. Consequently, this SPR engineering approach strongly couples the optical field with electronic excitations, enabling significant fluorescence lifetime reduction, enhanced quantum yield, improved UC efficiency, and precise control over emission directivity. By employing a tilted plasmonic nanocavity, Zheng and Zhang *et al.* achieved simultaneous compression of the f - f transition fluorescence lifetime in rare-earth-doped UCNPs to sub-50 ns and a thousand-fold enhancement in quantum yield^[42]. The asymmetric nanocavity structure and reinforced chiral photon local density of states enabled far-field directional emission and tunable chiral UCL. A key foundation for such precise control lies in the inherent optical anisotropy of building blocks like Au NRs, which exhibit orthogonal dual plasmonic resonance modes and polarization-sensitive near-field responses. Capitalizing on this anisotropy, Wu *et al.* designed a series of nanoantennae-load UCNP assemblies to achieve angularly polarized excitation and emission at the single-particle level^[44]. As shown in Figure 1f, each structure comprises one to three colloidal Au NRs, arranged at different coupling angles, coupled with an individual UCNP. These configurations demonstrated distinct polarization-dependent UCL modulation: under horizontal excitation, the plasmon resonance aligned with the UCNP's 660 nm emission band, leading to strong enhancement (up to 138-fold for the collinear dimer, CNC). Vertical

excitation, in contrast, resulted in weaker SPR coupling and diminished amplification. This work exemplarily translates the fundamental polarization response of a single Au NR into a programmable nanoantenna system, providing a direct pathway to regulate the interaction between the optical field and the $4f$ transition dipoles, thereby controlling both UCL intensity and polarization state. Kwon and Ko *et al.* developed a sophisticated hybrid photonic architecture: a microscale square lattice array composed of plasmonic dielectric microbeads (Figure 1g)^[25]. Each microbead was fabricated by decorating SiO₂ microbeads with Ag NPs, followed by the attachment of UCNPs (pMBs). This design synergizes dielectric resonance and plasmonic enhancement. The SiO₂ microsphere acts as a dielectric resonator, trapping NIR photons and enhancing visible emission through resonant modes. Concurrently, the attached Ag NPs functioned to extend the optical path, generate plasmonic hot spots for NIR absorption, and act as nanoantennas for scattering visible light. This cooperative mechanism resulted in a three order UCL enhancement under the weak NIR excitation relative to the reference platform. Liu *et al.* reported an on-chip plasmonic nanostructure in which UCNPs were site-specifically self-assembled into gold nanotrenches featuring sub-25 nm gaps^[43]. This precisely engineered nanogap cavity couples the UCNPs to confined gap-plasmon modes, strongly enhancing the anti-Stokes emission and overcoming the intrinsic inefficiency of photon UC in nanoscale systems. The system achieved 10⁵-fold UCL enhancement along with a 3.7-fold increase in spontaneous emission rate, both attributed to the extreme field confinement within the plasmonic hotspot.

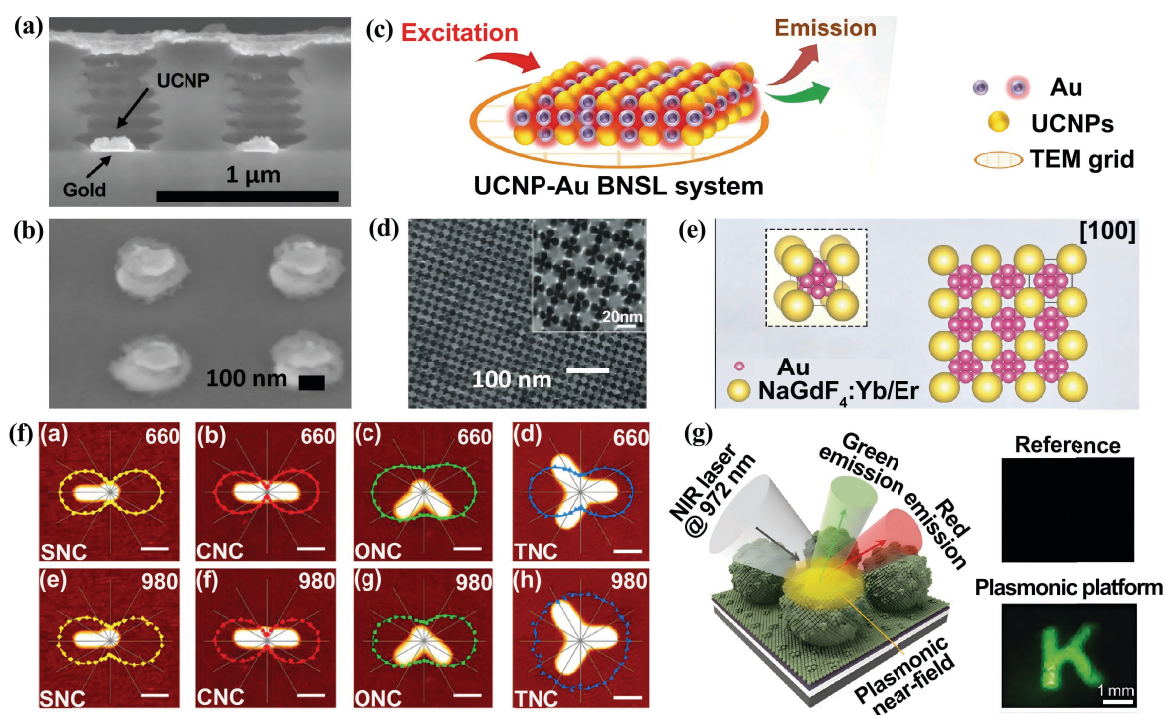


Figure 1. SPR engineering for UCL. (a-b) The cross-section SEM image of resist hole array template after UCNPs dropcast step (a) and angled SEM image of MIM after resist removal (b); (c) Schematic illustration for the preparation of 2D UCNPs-Au BNSLs through evaporation-driven growth; (d-e) The TEM image of UCNPs-Au BNSL isostructural with NaZn₁₃ phase (d), and its [100] projection (e); (f) AFM topographic images of nanoantennae-load UCNPs with different configurations and related polar plots of normalized UCL intensity; (g) The cross-section focused ion beam-SEM image of its 3D conceptual illustration. The pictures on the right show the experimental UCL from the pMBs compared to that of the reference structure. Republished with permission from^[24,25,40,41]. SPR: surface plasmon resonance; UCL: upconversion luminescence; SEM: scanning electron microscopy; UCNPs: upconversion nanoparticle; MIM: metal-insulator-metal; BNSLs: binary nanoparticle superlattices; AFM: atomic force microscopy.

The LSPR in heavily doped semiconductors arises from collective oscillations of intrinsic holes or excess free charge carriers introduced by high-level doping. In contrast to noble metal-based plasmonic materials, these semiconductor materials exhibit notably higher photochemical stability and lower carrier densities, resulting in LSPR absorption peaks that are predominantly located in the NIR region^[44-46]. Recent research has been dedicated to harnessing this semiconductor LSPR for UCL modulation, with a focus on elucidating the underlying physical mechanisms to guide the rational design of enhancement strategies. A representative study involves unique Cu_{2-x}S plasmonic quantum dots and their interaction with UCNPs^[47]. This work demonstrates that the LSPR in Cu_{2-x}S stems from surface ligand-confined carriers, exhibiting broadening, redshift, and diminution upon heating. An 8 nm MoO₃-spaced Cu_{2-x}S/MoO₃/UCNPs film enhances UCL and exhibits unusual power-dependent behavior (Figure 2a). A proposed model attributes the low-power enhancement to plasmonic scattering, whereas at high power it stems from two-photon excitation that enables electron diffusion into UCNPs within a < 50 nm range (Figure 2b,c). This mechanism, distinct from noble metal plasmons due to Cu_{2-x}S's band structure, offers new directions in plasmonics. Building on this foundation, our group further demonstrated that employing plasmonic semiconductor Cs_xWO₃ NPs significantly enhances both the luminescence efficiency and intensity of monolayer core-shell UCNPs^[48]. The in-situ morphology and optical properties of the hybrid structures were characterized using AFM and single-particle

optical imaging. By systematically optimizing the concentration of Cs_xWO_3 NPs, the thickness of the intermediate spacer layer, the excitation power density, and the design of the UCNP core-shell architecture, a maximum UCL enhancement of up to three orders of magnitude was achieved (Figure 2d). Both theoretical and experimental analyses further revealed that the near-field enhancement effect preferentially boosts UCL from the core region of the core-shell UCNPs, as recorded in Figure 2e,f. Large-area, oriented assemblies of Au@Ag core-shell NRs via a three-phase interfacial assembly strategy (Figure 2g,h,i)^[49]. These structures exhibited LSPR peaks centered at $\sim 1,550$ nm. Both experimental and theoretical analyses confirmed that the aligned NR arrays possess sharp LSPR bands and large scattering cross-sections. Upon coupling with UCNCs, a substantial enhancement in UCL was observed, accompanied by pronounced polarization selectivity with a degree of polarization reaching 0.72. Plasmonic antennas enable extreme local field intensification to address lanthanide ions' small absorption cross-sections, yet they suffer from intrinsic Ohmic losses, causing nonradiative heating and luminescence quenching^[50]. Topological insulators (e.g., Bi_2Se_3) mitigate this via surface plasmons with metal-like confinement, suppressed bulk losses, and intermediate Q factors (~ 100 – 150), enhancing UCL fields without severe quenching and bridging metallic and dielectric performance gaps^[51].

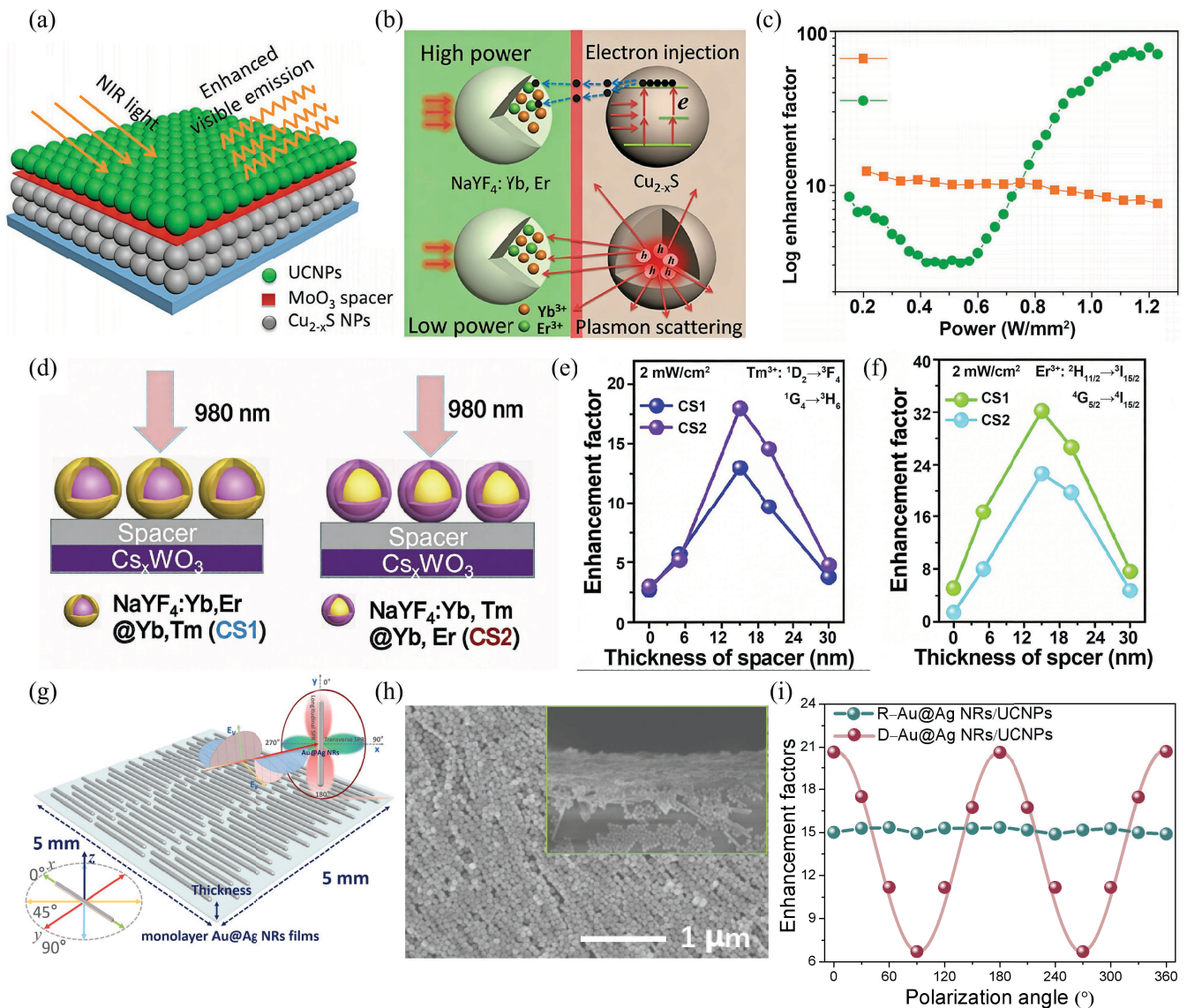


Figure 2. LSPR modulating UCL. (a–b) Schematic illustration of the $\text{Cu}_{2-x}\text{S}/\text{MoO}_3/\text{UCNPs}$ composite structure (a) and its power-dependent UCL enhancement mechanisms (b), showcasing distinct responses at high and low excitation power; (c) Enhancement factors of $\text{Cu}_{2-x}\text{S}/\text{MoO}_3/\text{UCNPs}$ and $\text{Au}/\text{MoO}_3/\text{UCNPs}$ film as a function of excitation power density; (d) Schematic illustration of the $\text{Cs}_x\text{WO}_3/\text{NaYF}_4/\text{monolayer-NaYF}_4:\text{Yb}^{3+}, \text{Er}^{3+}@\text{NaYF}_4:\text{Yb}^{3+}, \text{Tm}^{3+}$ (CS1) and $\text{Cs}_x\text{WO}_3/\text{NaYF}_4/\text{monolayer-NaYF}_4:\text{Yb}^{3+}, \text{Tm}^{3+}@\text{NaYF}_4:\text{Yb}^{3+}, \text{Er}^{3+}$ (CS2) hybrid structures; (e–f) Enhancement factors of Tm^{3+} and Er^{3+} ions emissions in $\text{Cs}_x\text{WO}_3/\text{NaYF}_4/\text{CS1}$ (e) and $\text{Cs}_x\text{WO}_3/\text{NaYF}_4/\text{CS2}$ (f), respectively; (g) Schematic of directional-Au@Ag NRs monolayer films; (h) Top-view SEM picture of directional-Au@Ag NRs/UCNPs hybrids, and the inset is the cross-sectional view of SEM; (i) Polarization dependence of UC enhancement factors of random-Au@Ag NRs/UCNPs and directional-Au@Ag NRs/UCNPs hybrids. Republished with permission from^[47–49]. LSPR: localized surface plasmon resonance; UCL: upconversion luminescence; NRs: nanorods; UCNPs: upconversion nanoparticles.

2.1.2 Photonic crystals (PCs)

The development of UC-based devices featuring micro/nano-engineered photofields represents a transformative approach for capturing low-energy photons and converting them into higher-energy emissions. Such structures have been shown to enhance UCL by several orders of magnitude. Nevertheless, energy dissipation and insufficient photon absorption typically result in excitation thresholds exceeding 1 mW/cm^2 , which surpasses retinal safety limits and restricts applications in wearable UC optics. Wang *et al.* demonstrated the integration of core-shell UC microspheres ($\sim 500 \text{ nm}$) that induce IR field convergence, $\text{NaYF}_4\text{:Yb, Er}$ shell-based resonant cavities for multipass reflection-absorption-upconversion cycles, and photonic crystal amplifiers, as shown in Figure 3a^[52]. IR field convergence intensifies local excitation flux to compensate for small $4f$ absorption cross-sections; multipass cycles extend light-matter interaction time, boosting $4f$ electron populations in excited states; PC amplification further elevates UCL via LDOS engineering. This configuration achieves a three-order-of-magnitude enhancement in UCL and an ultralow excitation threshold of 0.0025 mW/cm^2 . Implementing this system in UC contact lenses enhanced low-light imaging clarity and restored visual function in rabbits with retinal degeneration (Figure 3b,c). In Figure 3d,e, Hofmann *et al.* designed a 1D photonic structure comprising alternating layers of TiO_2 and poly(methyl methacrylate) (PMMA) polymer embedded with $\beta\text{-NaYF}_4\text{: }25\%\text{Er}^{3+}$ core-shell NPs. This Bragg stack architecture exhibits high interfacial uniformity and minimal surface roughness, which was constructed to experimentally validate a comprehensive theoretical model for predicting photonic enhancement of UC processes^[42]. The structure enabled systematic investigation of the interplay between photonic bandgap (PBG) effects, local density of states, and upconversion dynamics. As illustrated in Figure 3f, Lv *et al.* designed a composite nanosystem consisting of MnO_2 -modified UCNPs integrated with specially engineered PCs and polydimethylsiloxane (PDMS) array substrates^[53]. This structure was employed to enable dual-mode colorimetric and fluorescence detection of glucose with high environmental robustness and accuracy. The MnO_2 coating quenches the blue emission of the UCNPs until it is reduced by H_2O_2 , which is a product of glucose oxidation, leading to fluorescence recovery correlated with glucose concentration. The PCs-PDMS array, fabricated by depositing PMMA PCs on a hydrophobic PDMS glass substrate, selectively reflects blue light to minimize background noise and enhance signal specificity. This platform achieved significantly improved sensitivity ($1.2 \mu\text{M}$) and a broad linear range ($20\text{--}800 \mu\text{M}$), facilitating portable and high-performance glucose sensing in complex environments. Han *et al.* fabricated an inverse opal films (IOFs) constructed from shape-controlled NCs assembled via evaporative co-assembly with polystyrene template particles. These highly periodic, crack-free photonic structures demonstrate that precise control over nanocrystal morphology and assembly conditions enables the formation of high-quality IOFs with tunable optoelectronic and catalytic properties. They first established the method using TiO_2 nanocrystals of various shapes (rhombic, spherical, nanoplates), achieving ordered interstitial packing without high-temperature calcination to preserve nanocrystal integrity, as shown in Figure 3g. The approach was generalized to other functional nanomaterials, including indium tin oxide and zinc ferrite, producing crack-free films over $100 \mu\text{m}$ areas, with retained dopant distribution as confirmed by STEM-EDS (Figure 3h,i)^[26]. The resulting TiO_2 IOFs exhibited enhanced photocatalytic activity due to photonic slow-light effects, demonstrating the broad applicability of this multi-scale assembly strategy for advanced porous architectures. Gan *et al.* obtained PDs by utilizing van der Waals heterostructures formed by integrating few-layer n-type InSe with a silicon photonic crystal cavity patterned into a p-type silicon-on-insulator substrate (Figure 3j,k)^[54]. This structure was engineered to enhance frequency upconversion photodetection by strongly confining infrared light within a subwavelength air slot at the cavity center, thereby boosting nonlinear light-matter interaction in the InSe flake. Through the combined effects of resonant field enhancement and the intrinsic second-order nonlinearity of InSe, the device achieved efficient continuous-wave (CW) second-harmonic generation with pump power as low as $100 \mu\text{W}$. The generated SHG photons were absorbed across the n-InSe/p-Si junction, yielding a high UC photoresponsivity of 3.9 mA/W under pulsed excitation^[55]. As recorded in Figure 3l, Park *et al.* developed a dielectric 2D PC structure coupled with UCNPs, in which silica-coated UCNPs were selectively incorporated into a periodically structured Si_3N_4 membrane with subwavelength cavities. By leveraging PBG effects and resonant field localization rather than plasmonic enhancement, the structure amplified infrared pump fields within the nanocavities while avoiding metallic quenching. This approach yielded a remarkable 350-fold enhancement in red emission and 130-fold enhancement in green under CW excitation.

Local modulation of optical fields using plasmonic materials or PCs offers a promising approach to enhance UCL in UCNCs. However, current strategies are limited to static enhancement, and dynamic modulation of UCL remains unexplored, hindering its application in information processing devices. A dynamic UC modulation system was constructed using electro-responsive tungsten suboxide plasmonic photonic crystals (WO_{3-x} PPCs), as illustrated in Figure 4a,b. By integrating UCNPs with WO_{3-x} PPCs, we achieved reversible electric-field control ($\pm 1.6 \text{ V}$) over both the PBG and LSPR, leading to tunable enhancement of UCL by a factor of $\sim 5\text{--}26$ (Figure 4c,d,e,f). This modulation is attributed to voltage-dependent changes in the $\text{W}^{5+}/\text{W}^{6+}$ ratio, which alter the refractive index and oxygen vacancy concentration, thereby shifting the photonic and plasmonic resonances^[56]. The development of a bilayer PC film with dual stopbands enabled resonant enhancement of both excitation and emission in core-shell UCNPs, yielding over 150-fold fluorescence enhancement under low-power IR excitation (1.7 W/cm^2)^[59]. This facilitated ultrasensitive detection of prostate-specific antigen (detection limit: 0.01 ng/mL). Separately, in single-particle studies, a cascade amplifier integrating a PMMA PC with Cs_xWO_3 NPs produced a $\sim 1,600$ -fold UCL boost from a single UCNP (Figure 4g,h,i), demonstrating utility in sensing with a detection limit of 0.25 nM for dithiothreitol^[57]. Based on spectral management strategies, core-shell structured UCNPs excitable at both 808 nm and 980 nm were synthesized and subsequently assembled with PCs to amplify UCL. Leveraging this architecture, flexible dual-narrowband NIR

PDs were constructed using a PCs/UCNPs/MAPbI₃ hybrid design. These devices demonstrate remarkable detection performance, a low operational power threshold, and excellent mechanical flexibility, as summarized in Figure 4h,i,j^[58]. However, the primary limitation of PC-based UCL modulation is its narrow enhancement spectral bandwidth, which requires precise matching of the PBG to the excitation source and emitter's absorption lines, hindering broadband operation and practical integration^[60].

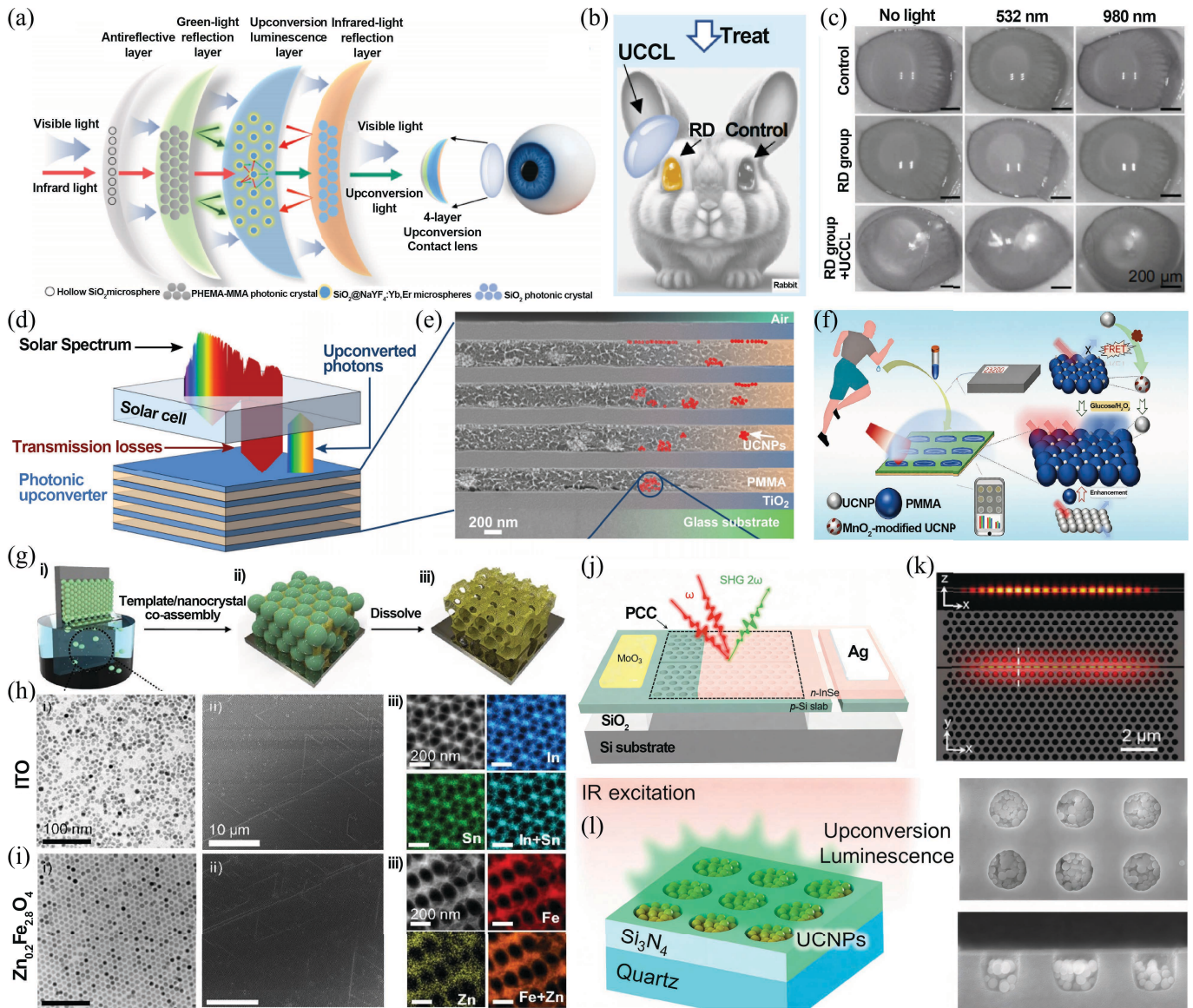


Figure 3. PCs modulating UCL. (a-b) Schematic illustration of the UCCL composed of microspheres (a) and its treatment of RD in rabbit eyes (b); (c) Images exhibiting pupil constriction from the control, RD, and RD with UCCL rabbits under the dark, 532 nm, and 980 nm light stimulation, respectively; (d) Utilization of sub-bandgap photons with a rear photonic upconverter for charge generation in solar cells; (e) The SEM image of a 1D TiO₂/PMMA PCs with embedded UCNPs; (f) Schematic of the MnO₂ modified UCNPs composites integrated with a PCs-PDMS array for dual-mode glucose detection; (g) Schematic of the evaporation-induced co-assembly process using pre-synthesized NCs; (h-i) Fabrication of highly ordered IOFs based on ITO (h) and zinc ferrite NCs (i) building blocks, respectively; (j-k) Schematic of the UC PDs based on an InSe/Si-PCC heterostructures (j) and its calculated distributions of electric-field $|E|$ of the resonance mode in the x-y and x-z planes (k); (l) UCNPs/2D Si₃N₄ PCs structure schematics and its high-magnification SEM image. Republished with permission from^[12,26,52-55]. PCs: photonic crystals; UCL: upconversion luminescence; UCCL: upconversion contact lens; RD: retinal degeneration; SEM: scanning electron microscopy; PMMA: poly(methyl methacrylate); UCNPs: upconversion nanoparticles; PDMS: polydimethylsiloxane; NCs: nanocrystals; IOFs: inverse opal films; ITO: indium tin oxide; PDs: photodetectors; Si-PCC: silicon photonic crystal cavity.

2.2 Resonant-mode management

2.2.1 Dielectric metasurfaces

In 1946, Purcell proposed a concise expression to evaluate the enhancement of the spontaneous emission rate by a resonant cavity under the weak-coupling regime, known as the Purcell factor. It is given by^[61]:

$$F_p = \frac{3}{4\pi^2} \cdot \frac{Q}{V_{eff}} \cdot \left(\frac{\lambda}{n}\right)^3 \quad (1)$$

where Q denotes the quality factor of the cavity, representing its ability to confine light in time, and V_{eff} is the effective mode volume, characterizing the spatial confinement of the electromagnetic field. The Purcell factor directly correlates the enhancement of spontaneous emission with the spatiotemporal confinement properties of the cavity, serving as a fundamental tool for understanding and studying light-matter interactions in optical resonators^[62,63]. In recent years, with the rapid development of micro-nano fabrication technologies, optical metasurfaces, as a class of artificially structured materials, have emerged as a key platform for controlling light fields at the subwavelength scale. As a breakthrough in subwavelength photonics, the foundational design principles of metasurfaces for arbitrary wavefront modulation were first established via geometric phase engineering, with early experimental realizations demonstrating unprecedented control over light reflection, refraction, and polarization at visible-NIR wavelengths^[64,65]. These pioneering works laid the groundwork for the subsequent development of metasurfaces in light-matter interaction engineering beyond the UCNF field. In plasmonic nanostructures, the V_{eff} is not constrained by the diffraction limit and can typically reach values on the order of $10^{-3}(\lambda/2n)^3$, which can be further reduced to $10^{-7}(\lambda/2n)^3$ through optimized design. Plasmonic nanocavities support highly localized optical fields and significantly enhanced light-matter interactions^[66-68]. Nevertheless, their performance is hampered by high ohmic losses in metals, which limit the Q to typically less than a hundred. This results in short photon lifetimes and substantial dissipation into heat or radiation. Furthermore, the extreme subwavelength V_{eff} constrains the flexible engineering of emission directivity and polarization. In contrast, dielectric PCs and metasurfaces exhibit fundamentally different behavior, as they leverage low-loss resonances to achieve high Q factors, albeit generally with larger mode volumes. The choice of material, dielectric or metallic, also critically influences the optical response. In all-dielectric realizations, a clear distinction emerges: PCs inhibit light propagation via PBGs, whereas metasurfaces locally tailor wavefronts through controlled phase, amplitude, or polarization modulation.

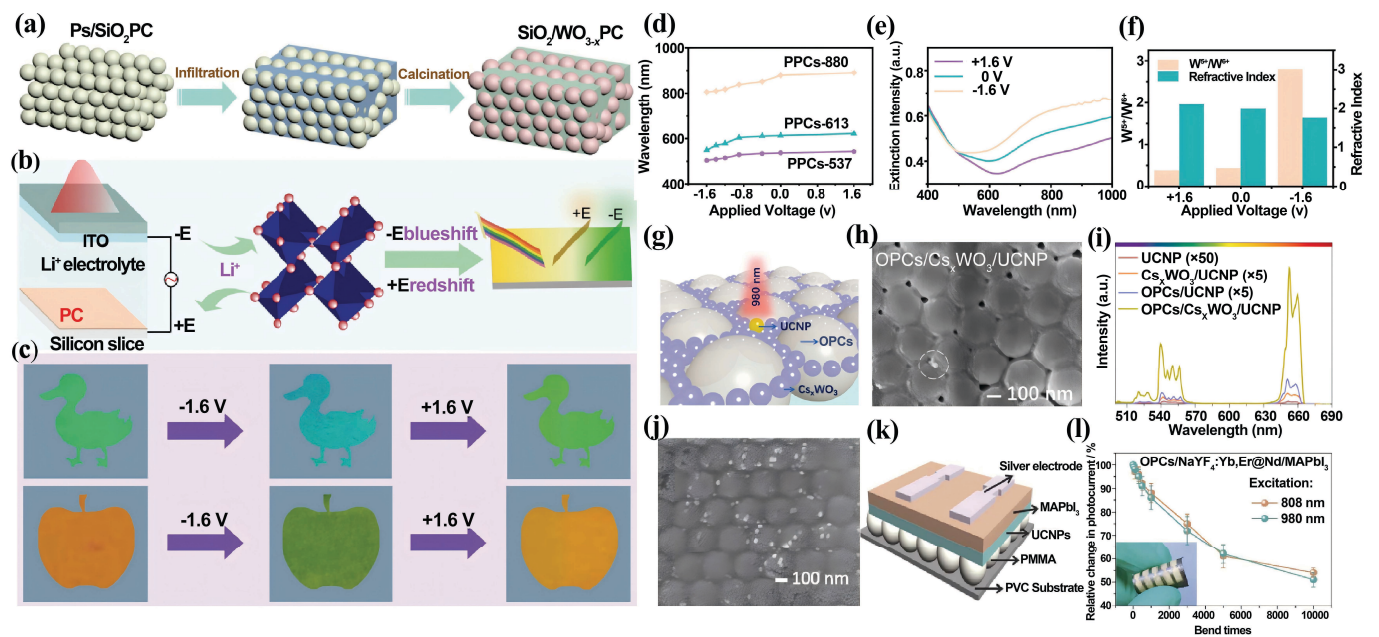


Figure 4. PCs modulating UCL. (a) Fabrication process of WO_{3-x} PPCs; (b) Electric-field modulation of the WO_{3-x} PPCs structures; (c) Optical appearance of WO_{3-x} PPCs before and after application of $\pm$ bias voltages; (d) Bragg wavelength of different WO_{3-x} PPCs as a function of applied voltage; (e) UV-vis-NIR absorption spectra of WO_{3-x} PPCs under the different potentials; (f) The corresponding variation of the ratio of W^{6+}/W^{6+} to the refractive index in WO_{3-x} PPCs under different bias voltages; (g-h) Schematic illustration of the OPCs/ Cs_xWO_3 /UCNP composite structure (g) and its SEM image (h); (i) UCL spectra in OPCs/ Cs_xWO_3 /UCNP hybrids structure and other comparison samples; (j) SEM image of PCs/UCNPs hybrids structure; (k-l) Schematic illustration of double narrowband NIR PDs based on PCs/UCNPs/ $MAPbI_3$ composites (k) and its photocurrents change with bending times (l). Republished with permission from^[56-58]. PCs: photonic crystals; UCL: upconversion luminescence; WO_{3-x} PPCs: electro-responsive tungsten suboxide plasmonic photonic crystals; UV: ultraviolet; NIR: near-infrared; OPCs: ordered photonic crystals; UCNPs: upconversion nanoparticles; SEM: scanning electron microscopy; PDs: photodetectors.

Bound states in the continuum (BICs) were originally proposed as eigenstates that remain localized despite existing within the continuous spectrum of propagating waves and were first experimentally realized in PCs and dielectric metasurfaces via symmetry protection^[69-71]. Quasi-BICs, the leaky counterparts of BICs with finite Q -factors, were later developed to enable practical resonant light-matter interactions, with pioneering non-UCNP works demonstrating their extraordinary ability to engineer light confinement and nonlinear optical responses in all-dielectric nanostructures^[72,73]. Exploiting the concept of quasi-BICs, Li's research team and

collaborators engineered a resonant TiO_2 metasurface that provides simultaneous electric field intensity enhancements up to 1,600-fold at two target wavelengths matching the emissions of UCNPs^[77]. As illustrated in Figure 5a,b, the metasurface's unit cell, a pair of nanobricks with a controlled orientation angle (δ), supports a polarization-dependent dual-resonance scheme, with a high-Q quasi-BIC at 660 nm and a stable Mie resonance at 540 nm (Figure 5c). This approach results in cross-polarization controlled UCL with exceptional brightness and polarization purity (> 0.86), as shown in Figure 5d. Li's demonstration of polarization controlled UC enhancement has been acclaimed for foreshadowing "transformative impacts" in merging metasurface optics with nanoscale light-matter interactions^[76]. Celebrano and colleagues engineered a nonlinear AlGaAs metasurface to achieve all-optical routing of upconverted light via interferometric control between third-harmonic and sum-frequency generation processes, demonstrating a remarkable routing modulation efficiency of up to 90% between different diffraction orders by tuning the relative phase of the pump beams^[77]. Zhao *et al.* designed an all-dielectric metasurface consisting of periodic silicon cylinders, which supports simultaneous electric and magnetic dipole resonances to enhance both the excitation field at 965 nm and the emission around 800 nm of UCNPs (Figure 5e,f)^[74]. By spatially matching the electric dipole mode with the UCNPs layer, a local field enhancement factor of ~ 73 times was achieved, contributing to an average upconversion signal enhancement of about 400-fold in experiment. While integrating multiple optical functions into a single metasurface remains challenging for advanced anti-counterfeiting, Yang *et al.* developed an anisotropic gap-plasmon metasurface incorporating UCNPs within its dielectric gaps, achieving triple-mode control of phase, amplitude, and luminescence^[78]. The UCNPs are embedded in the nanocavities, benefiting from the Purcell-enhanced local field to generate tunable upconverted emission under NIR excitation. Consequently, the same metasurface exhibits a polarization-switchable color image, a far-field hologram, and a luminescent image. This method also incorporates a physically unclonable function arising from the stochastic distribution of UCNPs, thereby significantly elevating security levels. While achieving broadband enhancement of nonlinear frequency conversion, particularly for widely separated pump and signal wavelengths, has long been constrained by poor mode-field overlap, Liu *et al.* designed a hyperbolic metamaterial composed of Au/ZnO multilayer triangular pyramids to overcome this challenge. As illustrated in Figure 5g,h,i, the structure's geometry (apex angle θ and base length a) tailors its hyperbolic dispersion, enabling an ultrabroadband slow-light effect in the mid-infrared (MIR)^[75]. This, combined with electric multipole resonances from gap-plasmon modes in the NIR, facilitates exceptional mode matching and strong field localization at the pyramid tips, thereby boosting MIR UC efficiency across a 3–5 μm band. Leveraging their low optical loss, structural design flexibility, and capacity for multi-resonant integration, dielectric superstructures have emerged as a premier platform for broadband UCL enhancement, which is an essential capability for matching incoherent light sources (e.g., sunlight). Key design strategies include gradient geometric parameter engineering to overlap discrete resonant modes (e.g., quasi-BICs, Mie/dipole resonances) into a continuous broadband enhancement window, and hyperbolic dispersion tailoring to achieve ultrawide slow-light effects and improved mode-field overlap across widely separated excitation/emission wavelengths. These approaches enable dielectric superstructures to harvest broadband photon flux from incoherent sources while maintaining high spatial control over local optical fields, addressing the narrowband resonance limitation of single-wavelength photonic structures for UCL engineering.

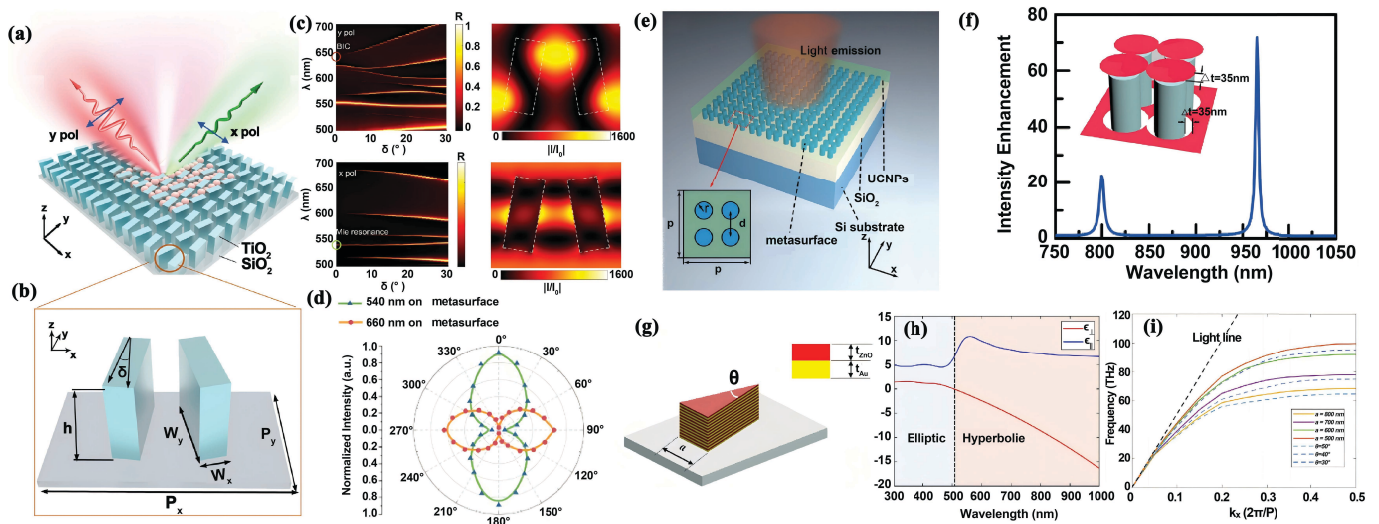


Figure 5. Metasurfaces modulating UCL. (a) Schematic of the UCNPs-integrated dielectric metasurface, which supports a high-Q quasi-BIC mode and a Mie resonance; (b) Unit cell design of the metasurface, featuring a pair of TiO_2 nanobricks with a tilt angle of $\delta = \pm 10^\circ$ on a SiO_2 substrate; (c) Resonance characterization of dielectric metasurfaces; (d) Highly polarized UCL from the metasurface-UCNP systems; (e) Unit cell architecture of the silicon metasurface. A periodic array of four-cylinder silicon clusters (period $p = 520$ nm) functionalized with a uniform layer of UCNPs; (f) Near-field intensity enhancement (~ 73 times at 965 nm) measured 35 nm above the metasurface (integration area in red, inset); (g) Schematic of the triangular prism unit cell; (h-i) Corresponding effective permittivity (h) and geometrically tunable dispersion relations (i), governing the slow-light behavior in the MIR. Republished with permission from^[27,74,75]. UCL: upconversion luminescence; UCNPs: upconversion nanoparticle; BIC: bound states in the continuum; MIR: mid-infrared.

Nonlinear metasurfaces based on multiple quantum wells (MQWs) exhibit exceptional second-order nonlinearities for frequency UC, yet their efficiency is fundamentally limited by intensity saturation under CW pumping. Nefedkin *et al.* overcame this limitation by introducing a counterintuitive pumping scheme that resonantly couples a strong pump field to unpopulated upper electronic subbands^[79]. Combined with an optimized MQW metasurface design, this approach suppresses saturation at practical intensity levels and significantly enhances MIR UC efficiency, and free from phase-matching constraints. They demonstrated a paradigm-shifting strategy by inverting the conventional pumping sequence to target unpopulated upper subbands (Figure 6a). This approach, integrated into a subwavelength trident-shaped metasurface resonator (Figure 6b), coherently channels x-polarized MIR waves into an enhanced intersubband nonlinear polarization, enabling high-efficiency Sum-Frequency generation without phase-matching requirements and sustaining saturation-free operation under CW excitation. Liu *et al.* reported strong upconverted circularly polarized luminescence (UC-CPL) from achiral core-shell UCNPs by leveraging a suspended bilayer gold metasurface with intrinsic chiral geometry, as illustrated in Figure 6c^[80]. The structure enabled both plasmonic enhancement and chirality transfer, yielding a record luminescence dissymmetry factor (g_{lum}) of 0.95 at 894 nm (Figure 6d). This high polarization contrast stems from resonant coupling between the metasurface's circular dichroism and the Nd^{3+} emission band, as confirmed by the distinct left- and right-handed circularly polarized (LCP and RCP) intensity profiles in Figure 6e. It is worth noting that, Kivshar *et al.* coupled rare-earth-doped UCNCs to a phase-gradient dielectric metasurface to demonstrate, for the first time, the photonic Rashba effect in upconversion photoluminescence^[81]. As conceptually illustrated in Figure 6f, the metasurface imposes spin-momentum locking on the emission, resulting in a directional splitting of LCP and RCP in momentum space. Stokes polarimetry analysis of the momentum-space distribution (Figure 6g) confirmed this effect, revealing that the ± 1 diffraction orders exhibit a high degree of circular polarization (up to 90%), in stark contrast to the unpolarized emission from the zeroth order. Würth *et al.* utilized large-scale nanoimprinted metasurfaces based on Si PC slabs to achieve a greater than 500-fold enhancement of emission from a UCN layer. By correlating the spectral response of the UCNCs with finite-element simulations, they further demonstrated the potential of this platform to map local field energies^[82]. Therefore, dielectric metasurfaces integrate efficient field localization, multifunctional wavefront control, and minimal absorption. Their design, however, typically relies on complex topological optimization and requires high fabrication fidelity, given that their resonant properties are highly sensitive to subwavelength geometric parameters^[83-85].

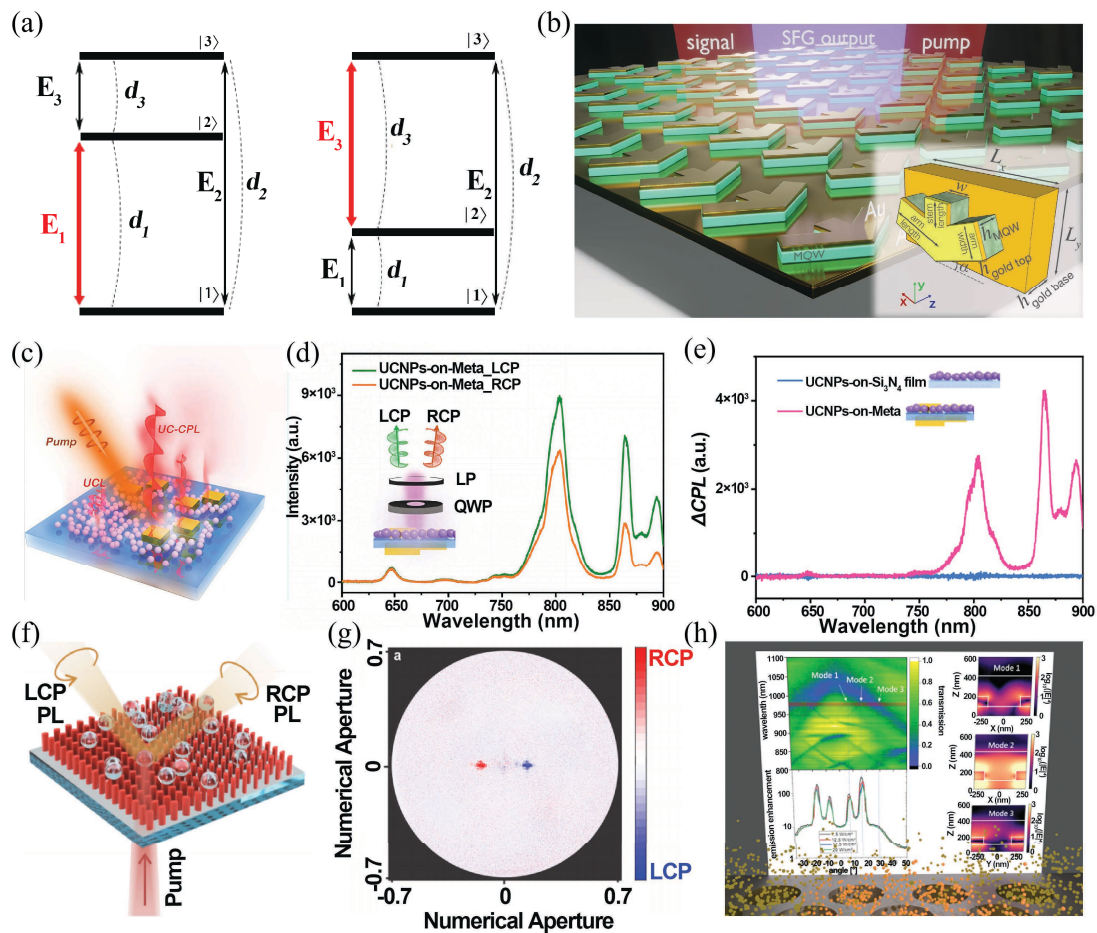


Figure 6. Metasurfaces modulating UCL. (a) 3-level system schemes modeling the subbands in a realistic MQW structure, the left and right diagram is conventional and the proposed scheme, respectively; (b) Unit-cell design and metasurface layout; (c) Structure diagram of UCN-coated chiral metasurface; (d) LCP and RCP UCL spectra from

UCNP-coated chiral metasurface; (e) Differentiated CPL spectra of UCNPs on chiral metasurface and blank membrane; (f) Photonic Rashba effect in upconversion photoluminescence. A phase-gradient dielectric metasurface coupled with UCNCs demonstrates spin-momentum locking of the emitted light; (g) Experimental demonstration of optical Rashba effect in UC photoluminescence; (h) Resonance characterization of the metasurface (110 nm) with a 200 nm UCNPs/PMMA coating, showing the resonant modes and excitation wavelength. Republished with permission from [79-82]. UCL: upconversion luminescence; MQW: multiple quantum wells; UCNPs: upconversion nanoparticle; LCP: left-handed circularly polarized; RCP: right-handed circularly polarized; UC: upconversion; PMMA: poly(methyl methacrylate).

2.2.2 Optical microcavities (whispering-gallery and Fabry-Pérot (F-P))

Optical microcavities constitute a foundational class of micro- and nano-scale structures that enable spatiotemporal confinement of light, drastically enhancing light-matter interactions and affording precise control over optical modes. These structures operate by trapping photons via reflection mechanisms, such as distributed Bragg reflection or total internal reflection, thereby enabling prolonged photon circulation and substantial resonant field enhancement. Based on their mode confinement mechanisms, optical microcavities are broadly categorized into F-P cavities, whispering-gallery mode (WGM), and PC cavities. This section focuses on the first two types. The performance of an optical microcavity is commonly quantified by its photon decay rate. In classical terms, stronger photon confinement leads to longer photon lifetimes and slower field decay. The performance of a microcavity is quantified by its quality factor Q , a dimensionless figure of merit. The attainable Q value is intrinsically dependent on the cavity architecture, leading to substantial variation across different designs. For instance, with comparable fabrication precision, F-P cavities typically exhibit Q factors on the order of 10^3 , whereas WGM can achieve values exceeding 10^6 , a difference spanning three orders of magnitude. There are various mathematical definitions of Q , depending on the physical context. It is most prevalent from the link between Q , the photon lifetime (τ_c), and the resonant mode frequency (ν), which can be calculated through following equation [86].

$$Q = 2\pi\tau_c = \frac{\nu}{\Delta\nu} \quad (2)$$

A higher Q corresponds to a stronger the limiting effect of the microcavity on photons, leading directly on a longer τ_c . Recent progress in semiconductor epitaxial growth techniques, particularly molecular beam epitaxy, has enabled remarkable improvements in the Q factors of optical microcavities. A representative achievement came in 2014 from the research group of Snoke *et al.*, who demonstrated an F-P microcavity based on a Distributed Bragg reflector structure with a Q factor reaching the order of 10^6 [87].

WGM resonators support stable electromagnetic resonances characterized by light waves circulating along a curved dielectric boundary via continuous total internal reflection. As illustrated in Figure 7a, resonance occurs when the optical path length of one complete round trip equals an integer multiple of the wavelength λ , leading to constructive interference of the recirculating light. For a microresonator of radius r , this condition is expressed by the following equation [89]:

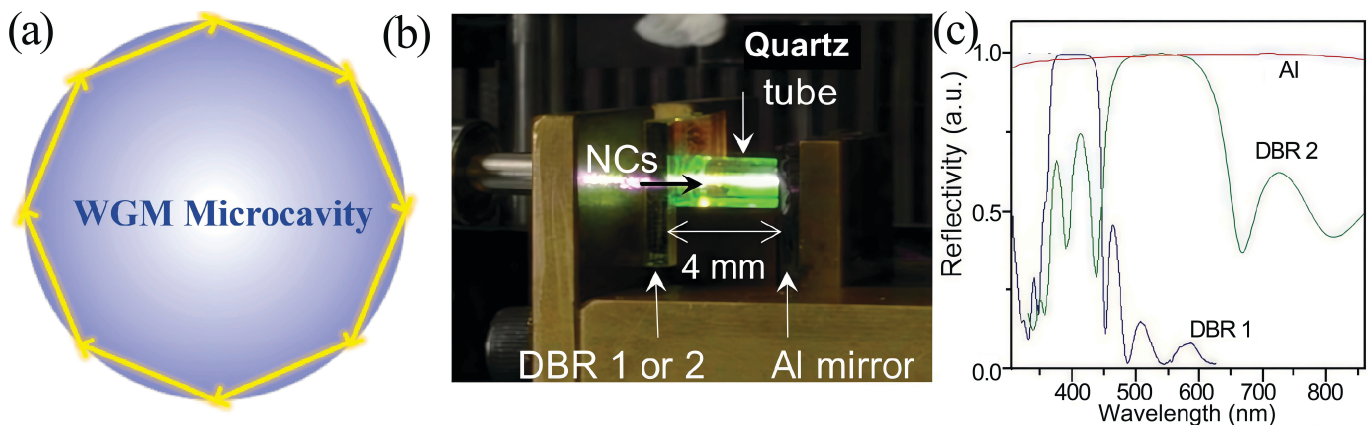


Figure 7. (a) Schematic diagrams of WGM; (b) Image of the F-P microcavity based on UCNPs gain medium; (c) Reflection spectra of DBR and the aluminum mirror. Republished with permission from [88]. WGM: whispering-gallery mode; UCNPs: upconversion nanoparticles; DBR: distributed Bragg reflector; F-P: Fabry-Pérot.

$$2\pi r \cdot n_{eff} = n_N \lambda \quad (3)$$

where n_{eff} is the effective refractive index of the mode, n_N is a positive integer representing the angular mode order, and λ is the resonant wavelength in vacuum.

A F-P microcavity is typically composed of two parallel planar mirrors. When these mirrors exhibit high reflectivity, light incident perpendicular to the mirror surfaces undergoes repeated reflections between them, resulting in photon oscillation along the cavity axis and a significant enhancement of the intracavity optical field. Denoting the cavity length as L_c and the refractive index of the intracavity medium as n_c , m is a positive integer, and the resonant wavelength λ satisfies the standing-wave condition [90].

$$\frac{n_c \lambda}{2} = m L_c \quad (4)$$

To achieve a high Q factor, distributed Bragg reflectors (DBRs) are often employed as an alternative to conventional planar mirrors. A DBR consists of a periodic stack of two or more semiconductor materials, arranged in an alternating ABAB sequence. Within each period, every layer has an optical thickness corresponding to a quarter of the resonant wavelength in the medium. Structurally, a DBR functions as a one-dimensional photonic crystal, efficiently reflecting light within its PBG due to the suppression of propagation. A key advantage of DBR-based semiconductor microcavities is the tunability of their PBG through geometric control of the period, while the reflectivity can be enhanced by increasing the number of repeating units. In such photonic crystal-derived cavities, the resonant frequency of confined photons is not solely governed by the cavity length and refractive index, but is strongly influenced by the bandgap properties of the DBR structure. Building on this principle, Zhu *et al.* constructed an F-P cavity featuring a quartz tube sandwiched between a DBR and an aluminum mirror, as illustrated in Figure 7b. A highly efficient core-shell UCNP solution served as the gain medium. By precisely tuning the reflectivity of the DBR and the aluminum mirror, the emission wavelength could be continuously shifted across the blue to red spectral regions, while the lasing linewidth was narrowed to a quarter of its original value (Figure 7c)^[88].

Dong and Ren *et al.* engineered a novel class of microsphere-based optical resonators by incorporating rare-earth ions ($\text{Yb}^{3+}/\text{Er}^{3+}$ or $\text{Yb}^{3+}/\text{Tm}^{3+}$) doped KY_3F_{10} and KMnF_3 UCNCs via high-temperature melting and crystallization^[91]. This judiciously tailored nanocrystal-in-glass architecture (Figure 8a) effectively minimizes optical scattering by controlling nanocrystal size below 50 nm and reducing the refractive index contrast with the host glass to under 0.05. The resulting composite microspheres exhibit high Q factors ($\geq 10^5$) across a broad size range. When optically pumped, these WGM-based systems show UC lasing under CW operation at room temperature, covering the full visible spectrum with distinct red, green, and blue emissions. The WGMs enhance light-matter interaction by extending photon residence time, amplifying stimulated emission from the $4f$ electron transitions of RE ions. This, combined with reduced scattering losses, cuts lasing thresholds by 45% and boosts slope efficiency fourfold compared with conventional systems, while the glass matrix ensures exceptional long-term stability by mitigating UCNC aggregation and surface quenching. It is worth noting that Shi *et al.* achieved simultaneous CW lasing across the ultraviolet, visible, and near-infrared spectra within a single ultrahigh Q factors ($> 10^8$) $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped silica microsphere, and the microcavity enables room-temperature upconversion lasing, through homogeneous rare-earth doping^[97]. Zhu's research group demonstrated low-threshold, six-photon UC lasing in high-quality ZnO microwire cavities^[92]. As illustrated in Figure 8b, they employed a vapor-liquid-solid method to synthesize well-faceted, hexagonal ZnO microwires, which function as natural WGM resonators. Under 2,100 nm femtosecond excitation, the system transitions from spontaneous emission to coherent lasing (Figure 8c), with near-field imaging revealing well-defined interference fringes that confirm coherent feedback establishment (Figure 8d). The system achieved a remarkably low lasing threshold of 220 GW/cm² for a six-photon process, attributed to the enhanced nonlinear interaction within the high Q factors ($\sim 1,000$) microcavity. Shu *et al.* demonstrated a record 24.6% UC quantum yield in a triplet-triplet annihilation (TTA) system by synergistically combining molecular design and optical microcavity engineering^[93]. They developed a heavy-atom-modified TADF sensitizer, BTZ-DMAC-4Br (Figure 8e), to enhance intersystem crossing. When the TTA solution was confined in cylindrical quartz capillaries, the formation of WGMs significantly boosted light-matter interaction, leading to a > 12 -fold efficiency increase over a conventional cuvette. As shown in Figure 8f, this cavity-enhanced UC was consistently high across capillaries of different diameters, underscoring the critical role of the WGM effect rather than merely the optical path length. Song *et al.* reported a mass-producible platform for ultraviolet-B (UVB) WGM lasing by integrating advanced nanocrystal design with scalable microcavity fabrication^[94]. They used core-shell-shell (CSS) UCNCs to enhance absorption and suppress competitive emission, then deployed substrate patterning and spin-coating process to form uniform, self-assembled microdisk arrays on SiO_2 pillars (Figure 8g). This approach enabled precise tailoring of laser performance through dimensional control of the microcavity. By fabricating microdisks with thicknesses below the cutoff for deep-UV wavelengths, competing emissions were selectively suppressed via waveguide-mode control, resulting in a low-threshold, spectrally pure UVB WGM laser. The resultant performance enhancement can be explained by a radiation model (Figure 8h). Moreover, dynamic regulation of two photon-pumped WGM lasing can be realized by exploiting the piezoelectric polarization effect in ZnO, as exhibited in Figure 8i. The microcavity achieves low-threshold UV coherent feedback (Figure 8j) via a nonlinear optical process, with the lasing wavelength being continuously tuned through externally applied strain^[95]. Through precise phase control, the in-situ precipitation of $\alpha\text{-NaYF}_4$ UCNCs creates a low-phonon environment that dramatically enhances the UCL of Ho^{3+} , enabling simultaneous lasing at 540, 650, and 750 nm within a high Q factor WGM. In Figure 8k,l, the glass-ceramic microcavity exhibits a two-order-of-magnitude intensity enhancement over its glass counterpart, while maintaining stable, well-defined mode structures across all emission bands^[96]. Kim *et al.* demonstrated a breakthrough in UC lasing through a laser-induced liquid-quenching technique that fabricates monolithic microspheres with an ultralow threshold (4.7 W/cm²) CW operation. The amorphous matrix created by rapid quenching exhibits atomic-scale disorder that effectively suppresses phonon-mediated energy back-transfer, enabling efficient population inversion. These microspheres serve as high Q factor WGMs with exceptional optical confinement (Figure 8m), supporting stable narrow-linewidth emission. Remarkably, the lasing wavelength can be continuously tuned over 3.56 nm through controlled variation of pump power and temperature (Figure 8n), exhibiting linear, reversible shifts while maintaining spectral coherence^[28]. Dong *et al.* reported a versatile tapered-fiber coupling strategy for achieving multi-wavelength UC

lasing in nanoparticle-coated silica microspheres. By uniformly depositing CSS $\text{NaYF}_4\text{:Tm}^{3+}\text{:NaYF}_4$ UCNPs onto an 11 μm microsphere, the system supports simultaneous WGM lasing across multiple Tm^{3+} transitions, from Vis to NIR, under the CW 980 nm excitation. An ultralow threshold of 0.61 μW was attained for the $^3\text{H}_4 \rightarrow ^3\text{H}_6$ transition, accompanied by a narrow linewidth and excellent stability over 180 minutes^[98].

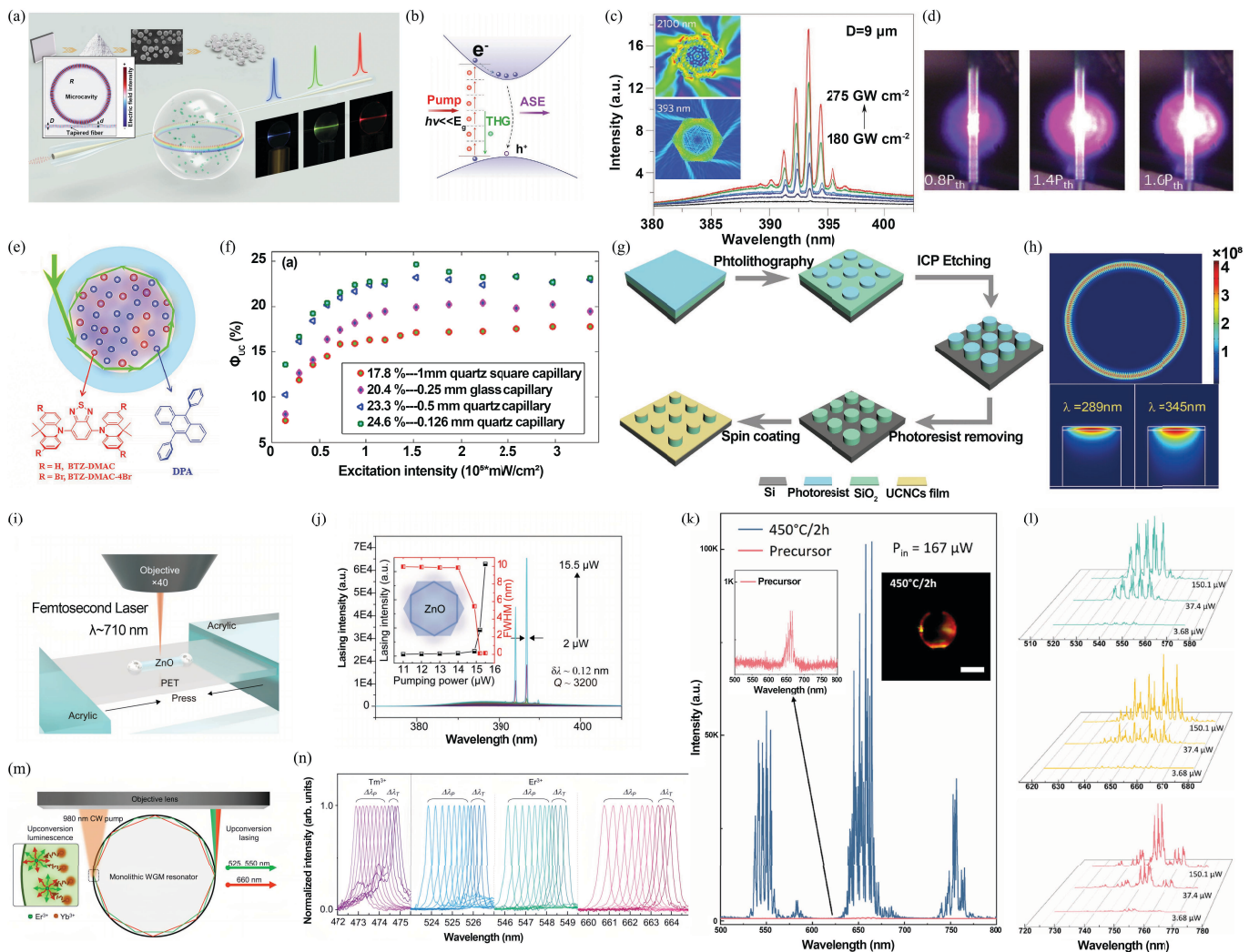


Figure 8. WGM modulating UCL. (a) Design and fabrication of nano-GC microsphere for infrared-to-upconverted Vis lasres. The schematic illustrates the GC microstructure and the powder melting/heating process used for their batch production. Also simulated electric field distribution at 980 nm in a microsphere (radius R) evanescently coupled to a tapered fiber (diameter D , gap d); (b) Schematic diagram for simultaneous multiphoton absorption UC lasing of ZnO microwires; (c) Cavity-enhanced nonlinear process in ZnO microwires resonator. With increasing excitation power, the emission spectrum evolves from a broad spontaneous profile to pronounced WGM lasing; (d) The near-field emission picture of single microwire under different excitation power. (e) The illumination of the light transmission in a WGM microcavity filled with the toluene solution of BTZ-DMAC-4Br/BTZ-DMAC and DPA (9,10-diphenylanthracene); (f) Upconversion quantum yield versus excitation intensity for BTZ-DMAC-4Br; (g) Schematic illustration of synthesis of microlaser array; (h) Theoretical modeling of WGMs and propagation loss; (i) Schematic of single ZnO microrod based two photon-pumped WGM lasing; (j) Power-dependent lasing characteristics; (k) UC lasing performance comparison. Spectra from the glass precursor (blue) and $\text{Ho}^{3+}/\text{Yb}^{3+}$ co-doped oxyfluoride (red) microcavities under 167 μW , 980 nm pumping; (l) Power-dependent lasing spectral evolution of $\text{Ho}^{3+}/\text{Yb}^{3+}$ co-doped oxyfluoride microcavities; (m) Schematic of UC lasing in liquid-quenched UC microspheres. Illustration of a 980 nm pump laser exciting WGM in the microsphere, leading to circulative amplification and visible emission via Yb^{3+} to Er^{3+} ET; (n) Emission spectra of spectrally tuned lasers. Republished with permission from^[28,91-96]. UCL: upconversion luminescence; GC: glass composite; WGM: whispering-gallery mode; UC: upconversion; ET: energy transfer.

Baldo *et al.* demonstrated an F-P microcavity strategy to dramatically enhance solid-state TTA UC under subsolar flux^[99]. As illustrated in Figure 9a, the cavity is constructed with a DBR and a silver mirror, confining an optical spacer and an upconverting layer containing PbS nanocrystal sensitizers. Through precise tuning of the cavity length, a resonant mode at 980 nm is established, yielding a 74-fold absorption enhancement and a 227-fold amplification of upconverted emission. Figure 9b reveals the optimized electric field distribution within the structure, confirming maximum field intensity localized in the active layer. This photonic engineering reduces the excitation threshold to 13 mW/cm² and boosts the external quantum efficiency (EQE), highlighting the vital

role of optical confinement in advancing low-intensity UC technologies. Yu and Yao *et al.* innovatively established 2D Ruddlesden-Popper perovskites (RPPs) as exceptional gain media for UC lasing through their unique quantum-confined architecture^[100]. The homologous RPP $(\text{PEA})_2(\text{MA})_{n-1}\text{Pb}_n\text{I}_{3n+1}$ ($n = 2$ and 3) microflakes exhibit a remarkable two-photon absorption coefficient of $3.6 \times 10^3 \text{ cm/GW}$, enabling efficient photon UC under 800 nm excitation at cryogenic temperatures. The natural formation of F-P microcavities between parallel crystal facets facilitates coherent feedback, with Figure 9c demonstrating sharp lasing emission at $\sim 598 \text{ nm}$ above a 1.2 GW/cm^2 threshold. Systematic investigation of cavity-length dependence in Figure 9d reveals well-defined mode spacing consistent with F-P resonance formation, while enhanced effective refractive indices indicate strong optical confinement.

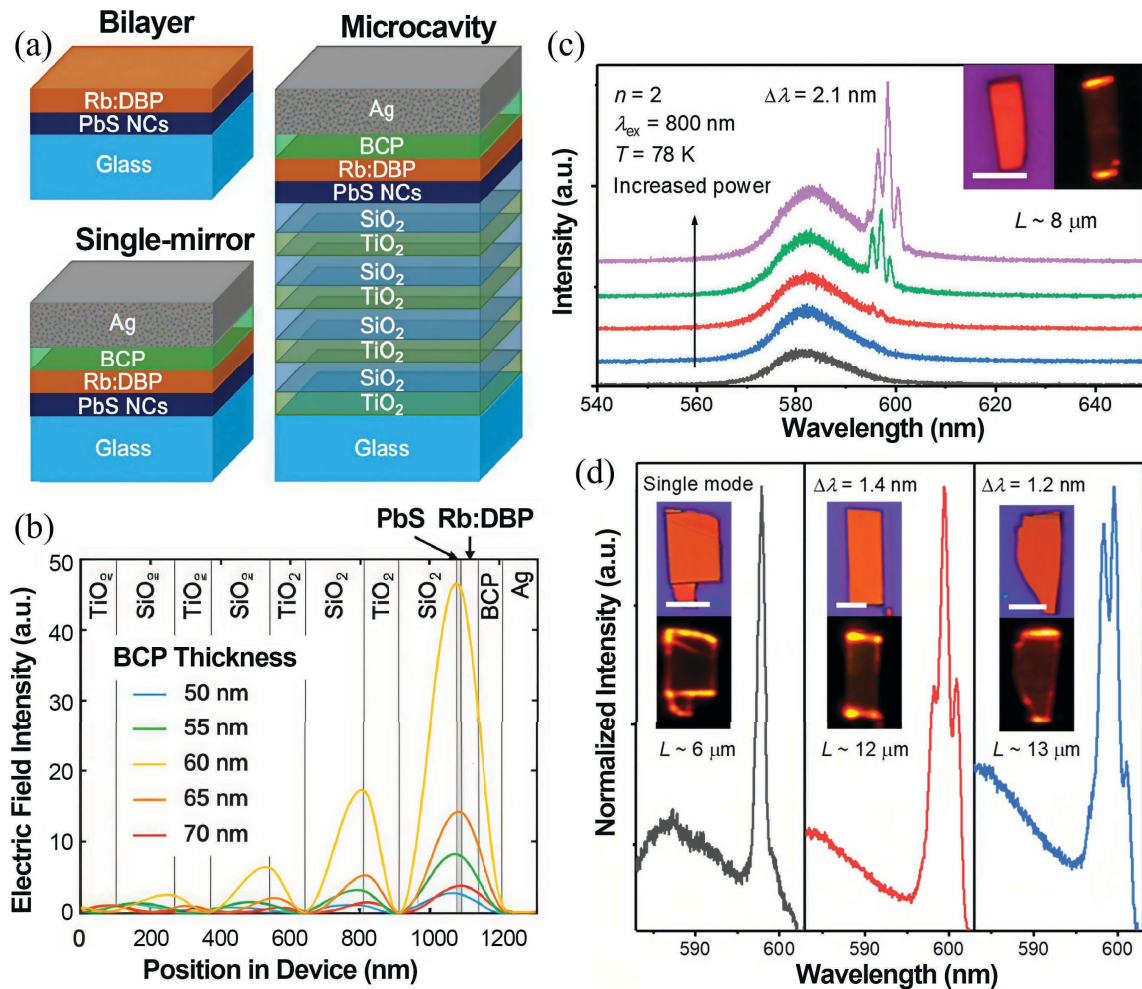


Figure 9. F-P microcavity. (a) Schematic illustrations of the bilayer, single-mirror, and F-P microcavity configurations; (b) Cavity-enhanced electric field. Cross-sectional electric field profile at 980 nm versus bathocuproine spacer thickness, showing maximum field intensity in the PbS layer at 60 nm cavity length; (c) Lasing characteristics of RPP ($n = 2$) flakes at 78 K with different cavity lengths (L). Power density-dependent lasing spectra, showing transition to coherent emission at 598 nm above threshold; (d) Cavity-length-dependent lasing spectra demonstrating F-P resonance tuning across flakes with different L . Republished with permission from^[99,100]. RPP: Ruddlesden-Popper perovskites; F-P: Fabry-Pérot.

2.3 Wavefront shaping

2.3.1 Microlens arrays

Composed of micro/nano scale optical elements, microstructure arrays derive their multifunctional capabilities from precisely engineered architectures that dictate light-matter interactions. Generally, optical microstructures include microgrooves, micropisms, and microlenses, which provide various optical functions due to their special geometrical features. Figure 10a categorizes fundamental types of microstructure arrays by their constituent element geometry. For arrays with unit dimensions spanning $0.5\text{--}5 \mu\text{m}$, optical behavior is governed primarily by refractive and reflective phenomena. These architectures enhance light-harvesting efficiency through multi-channel imaging, thereby enabling system miniaturization. Furthermore, the integration of heterogeneous array architectures facilitates advanced functions including precision beam steering and smart scanning capabilities, as illustrated in Figure 10b^[101].

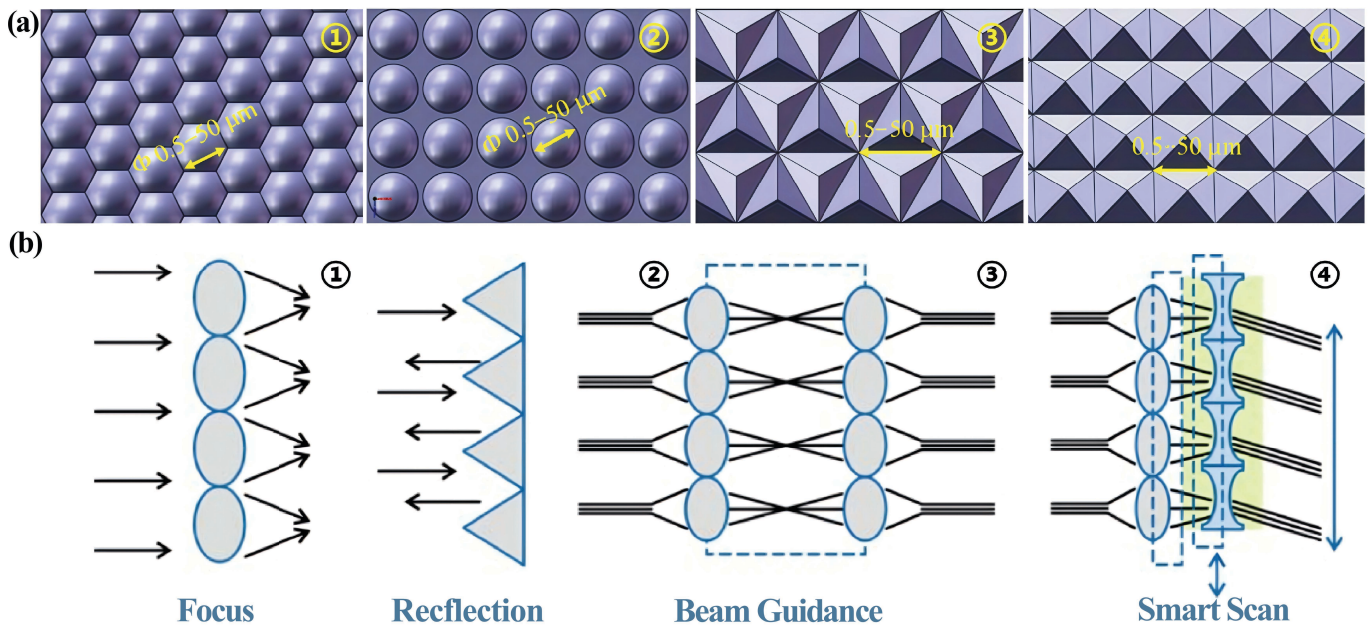


Figure 10. Structural characterization of microstructure arrays. (a) Element shape of microstructure arrays, where ①, ②, ③, and ④ separately represents adjacent MLAs, distributed MLAs, triangular pyramid arrays, and rectangular pyramid arrays; (b) Function and applications of microstructure arrays with large element size. Republished with permission from^[101]. MLAs: microlens arrays.

By taking advantage of the nonlinear excitation characteristics of MLAs, they can be utilized as an efficient photonic concentrator for boosting UCL at low pump levels. Liu *et al.* proposed to use polycarbonate MLAs to spatially modulate the excitation light, with a precisely defined period of $51.02\ \mu\text{m}$ and lens curvature of $16.47\ \mu\text{m}$ in height (Figure 11a,b), which functions as a non-invasive spatial light modulator that focuses incident NIR light into high-intensity micro-spots within the UCNPs layer. As illustrated in Figure 11c, the mechanism hinges on the power-dependent quantum yield of UCL, by amplifying the local excitation irradiance via lens induced light confinement, the MLAs drastically elevate the rate of multi-photon absorption processes. This leads to distinct enhancement factors for green and red UCL bands from Er^{3+} and blue UCL band from Tm^{3+} , consistent with their respective nonlinearity orders. Ray tracing simulations corroborate over two orders of magnitude local intensity gain, directly linking the geometric design of the MLAs to the enhanced photophysical dynamics^[29].

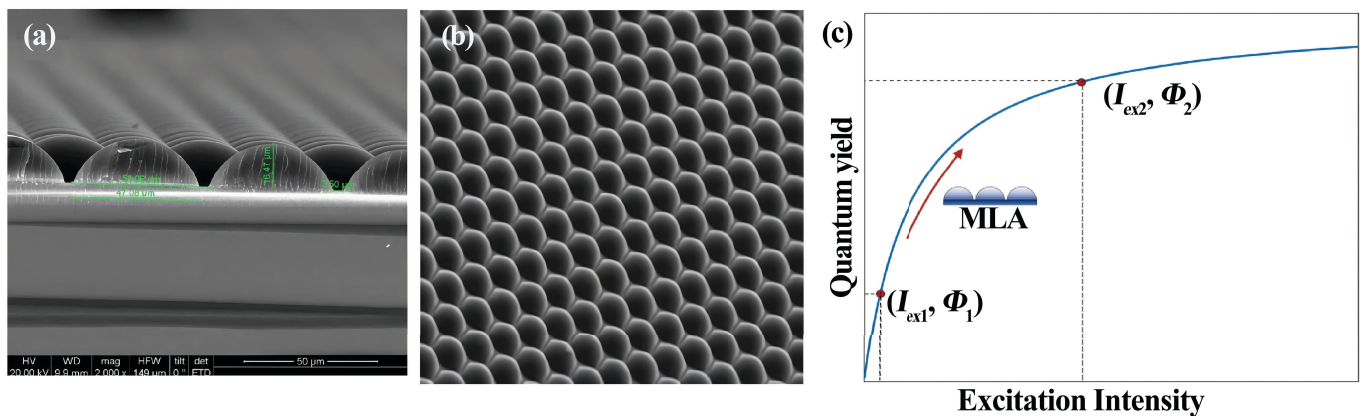


Figure 11. Polycarbonate MLAs for light focusing. (a-b) SEM images of the cross-section view (a) and top view (b) morphology of microstructure; (c) Schematic illustration of MLAs-enhanced quantum yield of UCL because of its nonlinear response to excitation intensity. Republished with permission from^[29]. MLAs: microlens arrays; SEM: scanning electron microscopy; UCL: upconversion luminescence.

Our group proposed a cascade optical field modulation strategy that synergistically integrates the superlensing effect of polymeric MLAs with the plasmonic resonance of Au NRs to achieve unprecedented UCL enhancement exceeding 10^4 -fold^[102]. As schematically illustrated in Figure 12a, the architecture sequentially couples far-field light strength through MLAs with near-field amplification via Au NRs. Systematic evaluation reveals that MLA-1, with optimized geometric parameters ($35\ \mu\text{m}$ diameter, $5.5\ \mu\text{m}$ height), provides $> 6,400$ -fold UCL enhancement across 808, 980, and $1,540\ \text{nm}$ excitation (Figure 12b). The synergistic combination with Au NRs further boosts enhancement factors to 2.4×10^4 , 2.2×10^4 , and 1.6×10^4 for 808, 980, and $1,540\ \text{nm}$ excitation, respectively (Figure 12c). In

Figure 12d, three-dimensional finite-difference time-domain simulations quantitatively validate the mechanism, showing MLA-1 generates 82.4-fold electric field intensification at 980 nm precisely within the UCNF layer, while the cascaded MLA/Au NR system achieves 157.8-fold field enhancement^[102]. This photonic approach enables construction of multispectral NIR narrowband PDs with record responsivities (> 30 A/W) and detectivities ($> 10^{11}$ Jones). Soon afterwards, Ko *et al.* presented a hierarchical plasmonic upconversion (HPU) architecture synergistically integrated with MLAs to achieve super-boosted UCL for highly sensitive 1,550 nm photodetection^[30]. The HPU film comprises a core-satellite Au nanoassembly that generates intense localized electromagnetic fields, yielding over 100-fold UCL enhancement. As quantitatively demonstrated in **Figure 12e**, the MLAs serve as a micrometer-scale light concentrator that focuses incident 1,550 nm radiation into the plasmonic hotspot region, further amplifying the local excitation field. This cascade optical modulation, combining MLA-assisted light condensation with plasmonic near-field enhancement, enables a detectable power limit as low as 0.03 mW/cm². Kimizuka and Yanai *et al.* demonstrated the pivotal role of MLAs in enabling Vis-UV UC under sub-solar irradiance. By integrating MLAs with an optimized UC porous film, the system based on quartz substrates achieves a remarkable reduction in excitation threshold to < 0.60 mW/cm², surpassing natural sunlight intensity^[103]. The MLAs function as photonic concentrators that focus incident light into micrometer-scale hotspots within the film, dramatically increasing local excitation density while maintaining the film's record UC quantum efficiency of 27.6%. As quantitatively demonstrated in **Figure 12f**, this optical field condensation strategy permits efficient TTA UC at irradiance levels previously inaccessible, establishing MLAs as essential components for practical solar-driven UC devices.

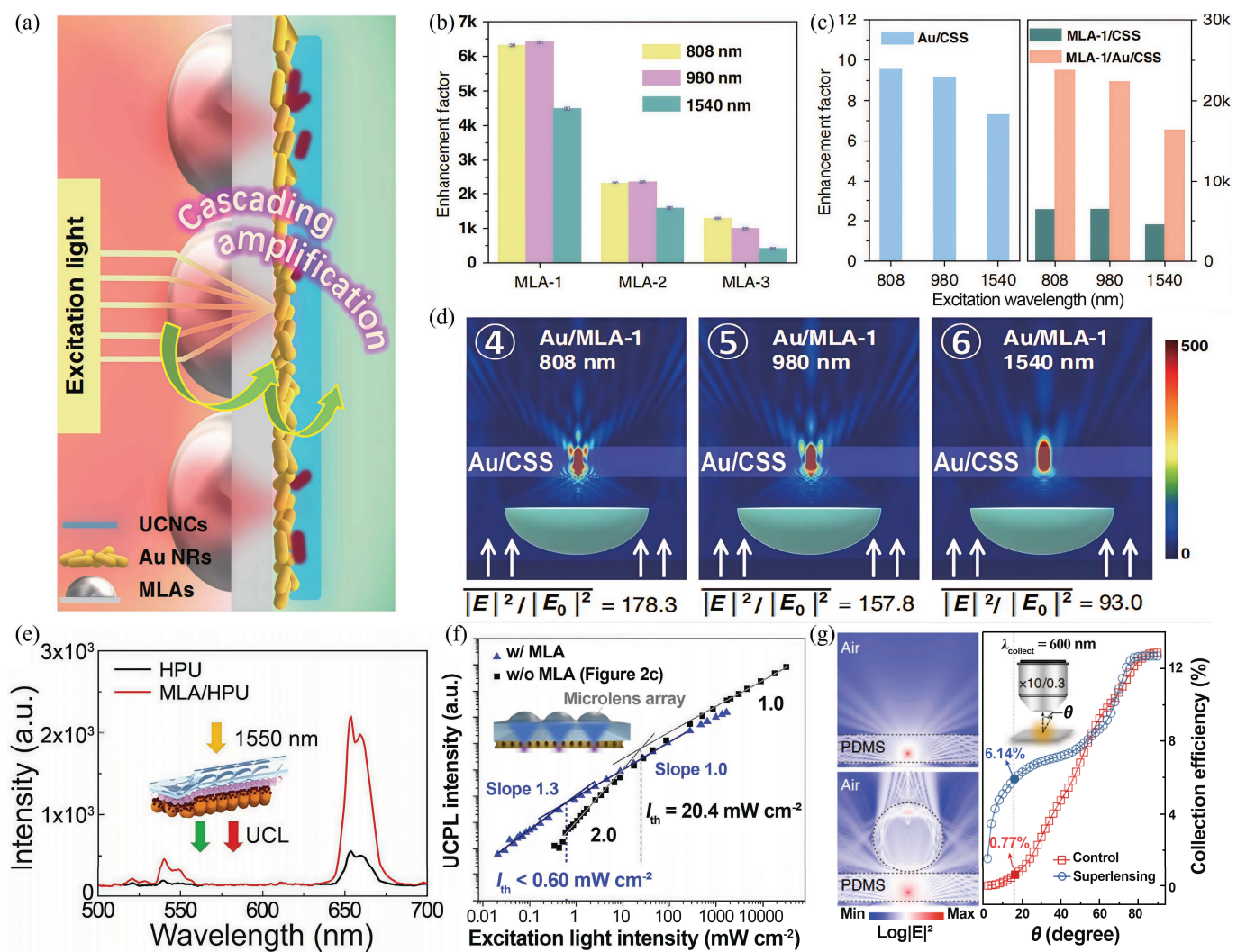


Figure 12. MLAs modulating UCL. (a-b) Schematic illustration of the cascading amplification strategy for UCNs; (b-c) Enhancement factors of MLA1-3 in MLA/CSS composites (a) and Au NR/CSS, MLA-1/CSS, and MLA-1/Au NR/CSS composites (b) at 808, 980, and 1,540 nm excitation, respectively; (d) Simulated electric field intensity distribution of Au/MLA-1 hybrid structures under the 808, 980, and 1,540 nm excitation; (e) The transmitted UCL spectra of HPU and MLAs/HPU under the 1,550 nm excitation at 24 mW/cm²; (f) Excitation power density dependent UCPL intensity of the film integrated with (blue) and without (black) MLAs; (g) Comparison of simulated far-field collection efficiency for UC emission with and without dielectric microbeads. Republished with permission from^[30,102-104]. UCL: upconversion luminescence; UCNs: upconversion nanocrystals; MLA: microlens array; CSS: core-shell-shell; NR: nanorod; HPU: hierarchical plasmonic upconversion; UCPL: upconversion photoluminescence.

Liu *et al.* established a paradigm for nonlinear photonic amplification through dielectric MLAs, demonstrating up to 10^5 -fold UC enhancement via dual-wavefront engineering. The dielectric microbeads function as bi-functional optical elements that simultaneously concentrate excitation energy into subwavelength hotspots and collimate highly divergent emission^[104]. As critically evidenced in Figure 12g, the microbeads transform the isotropic UC emission into a collimated beam, enhancing collection efficiency approximately eightfold through effective wavefront shaping. This synergistic interplay between excitation intensification and emission extraction operates independently of Purcell effects, distinguishing it fundamentally from plasmonic or cavity-based enhancement strategies.

2.3.2 Liquid-crystal modulators

Liquid-crystal spatial light modulators (LC-SLMs) represent programmable micro-/nanophotonic devices for optical-field engineering. By leveraging the electrically tunable birefringence of liquid crystals, LC-SLMs enable precise, dynamic control over the phase, amplitude, and polarization of an excitation beam at the microscale. This capability provides a direct pathway to enhance UCL by structuring the excitation field to maximize absorption and by tailoring the photonic environment to influence emission properties^[105–108]. A compelling demonstration of this approach is the generation of UC-CPL from intrinsically achiral UCNPs, which is a significant challenge since their negligible native dissymmetry factor ($|g_{lum}|$) limits their utility in chiroptical applications. While embedding UCNPs in static chiral matrices (e.g., cholesteric liquid crystals, CLCs) can impart chirality, this method often lacks dynamic reconfigurability and can suffer from nanoparticle aggregation. LC-SLMs offer a transformative all-optical strategy. By imprinting a designed helical phase front onto the excitation beam, LC-SLMs directly induce chiroptical interactions at the absorption stage. This bypasses material compatibility constraints and grants real-time control over the handedness and intensity of UC-CPL, enabling enhanced $|g_{lum}|$ and dynamic chiroptical devices^[109,110].

This synergy is exemplified in hybrid architectures. For instance, an aligned film of upconversion nanorods can function as both a polarized emitter and an alignment layer for a CLC, forming a superhelical structure that converts linearly polarized UCL into pure CPL within the CLC's PBG, with output tunable via external stimuli (Figure 13a)^[34]. Beyond polarization control, the wavefront-shaping capability of LC-SLMs can be broadly applied to enhance UCL intensity and directionality through optimized excitation patterns, such as focused arrays, that increase the effective excitation volume and local field intensity. Recent advances extend this dynamic control to TTA upconversion. For example, integrating sensitizers and chiral annihilators within a liquid crystal matrix has enabled tunable multi-color UC-CPL via a “one-excitation-to-multiple-emission” process (Figure 13b). Such systems can overcome triplet energy barriers and allow continuous color tuning alongside amplified circular polarization ($|g_{lum}| \approx 1.0$), as shown in Figure 13c^[107]. Ren *et al.* developed a metasurface-based optically addressed spatial light modulator capable of direct light-by-light modulation via nonlinear polarization control. This ultrathin (400 nm) platform integrates gold chiral nanostructures with a 300-nm ethyl-red azo polymer layer^[111]. The metasurface's L-shaped slit array provides precise polarization manipulation, while the photoswitchable polymer allows dynamic resonance tuning under milliwatt-level write light (532 nm). This architecture achieves exceptional resolution (500 lp/mm), surpassing commercial SLMs by an order of magnitude, while maintaining subwavelength thickness. Duan *et al.* demonstrated a sophisticated chiral LC modulator system that achieves tunable, multi-color UC-CPL through a “one-excitation-to-three-emissions” mechanism. By co-assembling a triplet sensitizer (PtTPBP) and two chiral annihilators (R/S-DPA and R/S-BDP) within a nematic host, the chiral annihilators induce the formation of a chiral nematic (N*LC) superstructure helix, serving as an effective chiral matrix^[112]. The system overcomes a significant triplet energy barrier (130 meV) via thermally activated triplet-triplet energy transfer, enabling two independent TTA-UC pathways. Under 635 nm excitation, this design simultaneously generates blue and yellow upconverted emissions from the annihilators, alongside a near-infrared downshifting emission from the sensitizer, all exhibiting circular polarization. Crucially, fine-tuning the annihilator ratio allows continuous color tuning of the UC-CPL across the blue-to-yellow range while amplifying the luminescence g_{lum} to 0.6, which is a 2.5-fold enhancement over the prompt value.

3. Optoelectronic Application Based on Light-Field Regulation

3.1 Photodetectors

UCNCs, featuring large Stokes/anti-Stokes shifts and excellent photostability can efficiently convert NIR photons into UV/Vis photons for absorption by narrow-bandgap semiconductors. Owing to their narrowband NIR wavelength-selective absorption, UCNCs serve as exceptional photosensitizers, offering a promising solution for developing next-generation wavelength-selective PDs (Figure 14a,b)^[102]. Our group demonstrated a strategy to enhance the luminescence of monolayer UCNPs by coupling them with semiconductor plasmonic Cs_xWO_3 NCs for narrowband NIR photodetection. The morphology and optical properties of the monolayer UCNPs were characterized in-situ using AFM and single-particle optical microscopy. Through systematic optimization of the Cs_xWO_3 concentration, intermediate-layer thickness, excitation power density, and core-shell architecture, the total UCL intensity was enhanced by three orders of magnitude. Experiments confirmed that the core-shell design yielded a stronger local-field enhancement effect on the core of the UCNPs. The optimized heterostructure was integrated into a 980 nm narrowband PD (bandwidth ~20 nm), achieving a R of 0.33 A W^{-1} , a D^* of 4.5×10^{10} Jones, and a response time of ~100 ms (Figure 14c,d). Furthermore, hydrophobic UCNPs were employed as a coating layer that also acts as a moisture barrier, significantly improving the device's

long-term environmental stability. After 100 days of storage, the photodetector retained ~70% of its initial performance, markedly outperforming the control MAPbI₃/UCNPs device^[48]. Zhang *et al.* devised an elegant hybrid approach by integrating disordered metasurfaces with UCNPs, thereby enabling efficient IR detection on a Si platform. As shown in Figure 14e, the metasurface, composed of hybrid Mie-plasmonic nanocavities, provides simultaneous near-field localization and broadband absorption enhancement. This disordered architecture not only traps incident IR light but also boosts the UC efficiency of the UCNPs (NaYF₄: Er@NaYF₄), which convert IR photons into Vis wavelengths. The resulting Vis photons are then efficiently collected by Si substrate via a Schottky barrier, leading to a strong photocurrent response. The practical demonstration of this concept is illustrated in the measurement schematic (Figure 14f), where the metasurface-UCNP device is wired for optoelectronic characterization. Under 1,550 nm illumination, the optimized device achieved a R of 0.22 A W⁻¹ at room temperature, and corresponding to an EQE of 17.6%, thus extending Si's operational range well into the IR^[113]. Subsequently, a CSS architecture was engineered within the UCNs. Through selective RE³⁺ doping, distinct Vis emission bands could be activated under NIR excitation at 808, 980, and 1,540 nm. This spectral selectivity enabled the development of a PD with separable multi-band optical channels. The working principle relies on the wavelength-dependent frequency response of the UCL, when the excitation intensity is modulated, both the decay rate and the modulation depth vary characteristically with the incident NIR wavelength. By analyzing the photoresponse to different modulation frequencies, the excitation wavelength can be identified, thereby achieving selective multi-band photodetection (Figure 14g,h). As mentioned earlier (Figure 12a,b,c,d), benefiting from this cascaded optical-field regulation, the detector exhibited significantly enhanced performance, with R and D^* reaching 30.73 A W⁻¹ and 5.36×10^{11} Jones at 808 nm, 23.15 A W⁻¹ and 3.45×10^{11} Jones at 980 nm, and 12.2 A W⁻¹ and 1.91×10^{11} Jones at 1,540 nm, respectively. To circumvent the complex synthesis and harsh conditions often required for high-quality plasmonic-UC hybrids, Park *et al.* developed a streamlined one-pot hydrothermal method to prepare UCNPs@Au composites^[102]. This approach used a binary functional EDTA salt as both surfactant and reducing agent, enabling the insitu growth of Au on UCNPs. The composites were further conjugated with Prussian blue (PB) to form UCNPs@Au+PB nanocomposites. This architecture induced a 21-fold quenching of UCL via FRET, while the synergistic combination of PB, Au, and UCNPs effectively reduced carrier traps ($\alpha \approx 0.85$) and enabled ultrasensitive broadband detection across 432–980 nm. The device architecture of the resulting PD is illustrated in Figure 14i (3D schematic) and Figure 14j (side view), which show a two-terminal, gate-free structure based on the NC/epitaxial graphene/SiC hybrid. The photoresponse spectrum (Figure 14k) further revealed a high response at 980 nm^[114]. The enhancement mechanism stems from Au plasmons boosting the one-photon absorption of Er³⁺ ions, while PB provides broad optical absorption and increases the carrier density.

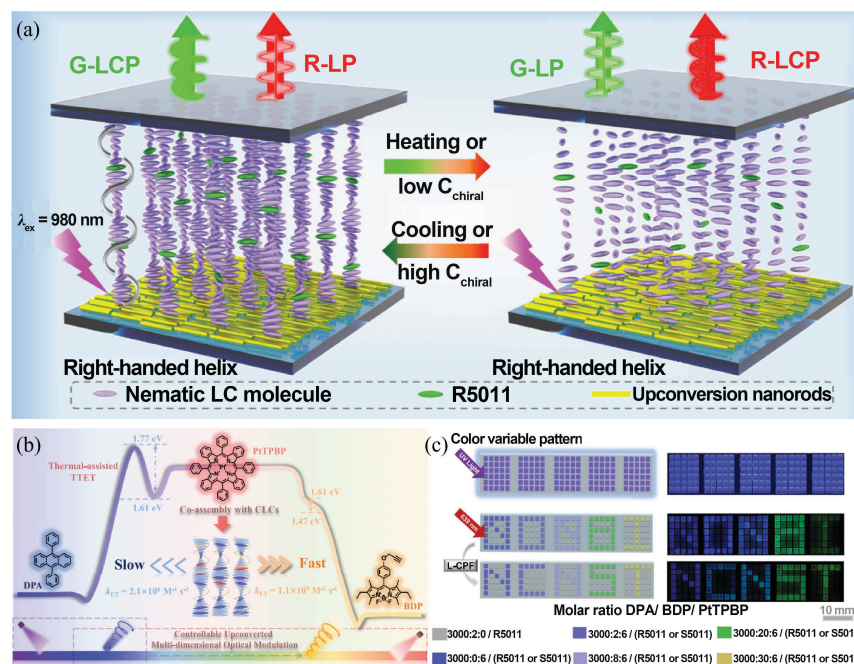


Figure 13. Liquid-crystal modulators UCL. (a) CLC-UCNR hybrid structure and its polarization output. Diagram showing aligned UCNRs within a right-handed CLC matrix, where the helical superstructure converts intrinsic linearly polarized emission from nanorods into circularly polarized light via the PBG effect, yielding both CP and LP emission channels; (b) The chiral dual-annihilator system for controllable photon upconversion. Triplet-energy competition between two annihilators, mediated by thermally activated triplet energy transfer, enables multi-dimensional tuning of UC-CPL colour, distinguishable from downshifting CPL by excitation wavelength; (c) The anti-counterfeiting application based on the micro-matrices of the chiral dual-annihilator model. Republished with copyright permission from^[31,107]. UCL: upconversion luminescence; CLC: cholesteric liquid crystal; UCNR: upconversion nanorods; PBG: photonic bandgap; CP: circularly polarized; LP: linearly polarized; UC: upconversion; CPL: circularly polarized luminescence.

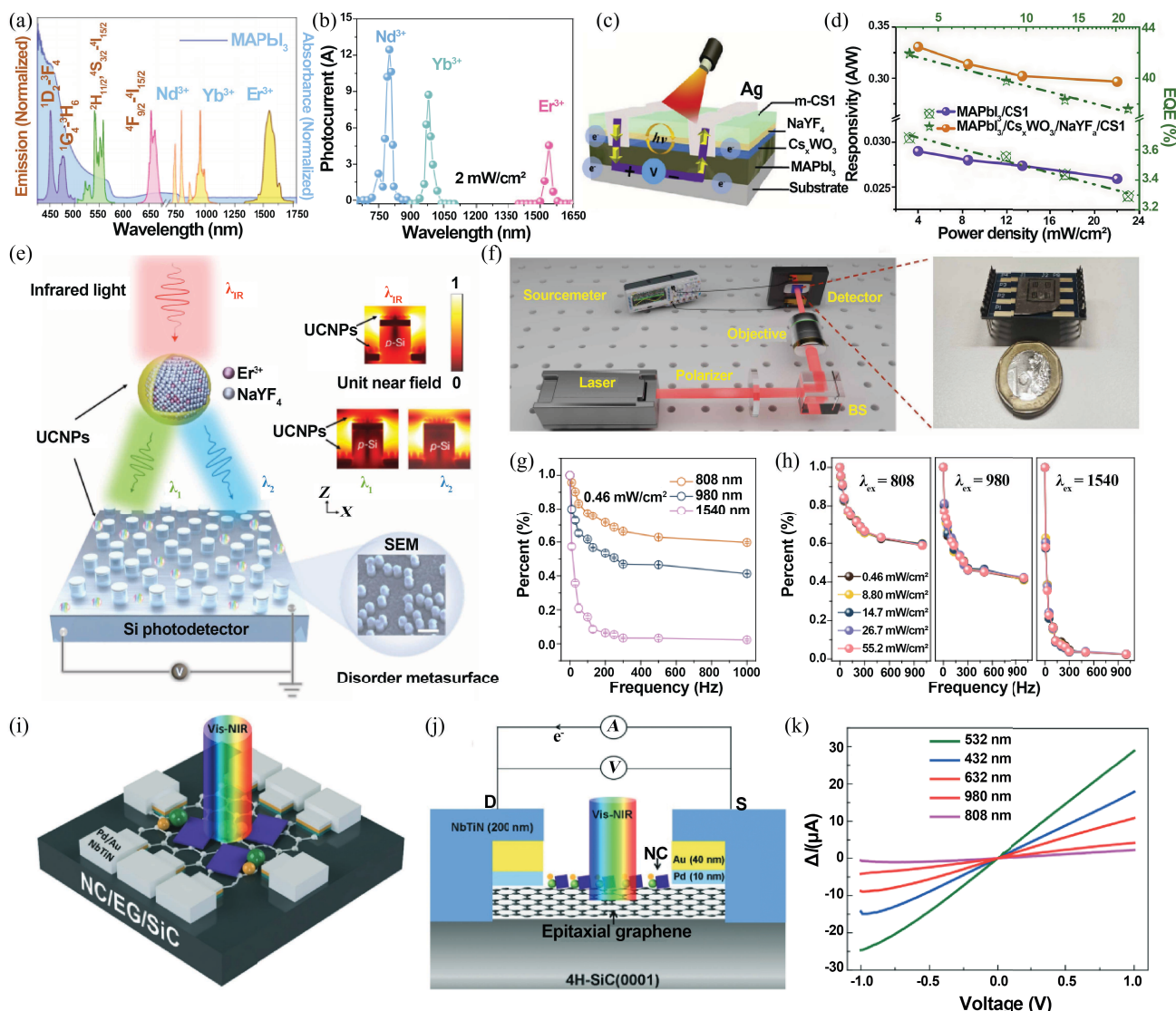


Figure 14. Optical field modulated UCNcs-based PDs. (a) Absorption of perovskite (MAPbI₃) films, Nd³⁺, Yb³⁺, and Er³⁺ and emission spectra from ¹D₂ → ³F₄, ¹G₄ → ³H₆, ²H_{11/2}, ⁴S_{3/2} → ⁴I_{15/2}, and ⁴F_{9/2} → ⁴I_{15/2} transitions in core-shell-shell structured UCNcs; (b) Photocurrent response of the MLA/Au NRs/core-shell-shell UCNcs/MAPbI₃ device under irradiance with 650-1,650 nm light; (c) Schematic illustration of NIR PDs at 980 nm based on the MAPbI₃/Cs_xWO₃/NaYF₄/CS1 hybrid structures; (d) Power dependence of *R* and *EQE* of MAPbI₃/CS1, and MAPbI₃/Cs_xWO₃/NaYF₄/CS1; (e) Schematic of the disordered metasurface integrated with UCNcs for enhanced light absorption at Vis (λ₁ = 550 nm, λ₂ = 650 nm) and NIR (λ_{IR} = 1,550 nm) wavelengths. Scale bar of the SEM image is 500 nm; (f) Schematic of the optoelectronic response measurement setup and a photograph of the fabricated detector alongside a 1 SGD coin; (g-h) Relative UCL intensity upon changing the excitation light of 808 nm, 980 nm, and 1,540 nm frequency (g) and simultaneously varying the excitation power density (h); (i-j) 3D schematic (i) and side view of NC/EG/SiC hybrid PD, which including source/drain electrodes connected to measurement units (j); (k) Δ*I* as a function of source-drain voltage (V_{DS}) for the PDs under broad-range illumination (432-980 nm, 3,184 μW cm⁻²). Republished with permission from [48,102,113,114]. UCNcs: upconversion nanocrystals; PDs: photodetectors; MLA: microlens array; NRs: nanorods; NIR: near-infrared; *EQE*: external quantum efficiency; UCNcs: upconversion nanoparticles; SEM: scanning electron microscopy; SGD: Singapore dollar; UCL: upconversion luminescence; EG: ethylene glycol; SiC: silicon carbide.

3.2 Solar cells

Notably, by transforming sub-bandgap NIR photons into usable above-bandgap light, UCNcs present an exciting opportunity to minimize non-absorption losses and surpass the Shockley-Queisser limit in photovoltaics [115,116]. In 2018, our group innovatively integrated UCNcs for broadband spectral harvesting in perovskite solar cells (PSCs) to extend the spectral response into NIR region [117]. A composite multilayer film of UCNcs/Ag was integrated on the rear side of a transparent PSC via pulsed laser deposition. This architecture leverages the synergistic effects of engineered UCNcs and LSPR from Ag, effectively converting unused NIR photons into visible light that is harvested by the perovskite absorber. Concurrently, a down-conversion (DC) layer using the europium complex Eu(TTA)₂(Phen)MAA was applied on the front side to manage ultraviolet photons. The coordinated UC/DC system, combined with a novel NiO/Ag/NiO transparent electrode, yielded a remarkable power conversion efficiency (PCE) of 19.5% and a short-circuit current density of 27.1 mA/cm². Building upon the strategy of UC spectral management, subsequent research in our group further

addressed the intrinsic limitations of low quantum yield and narrow absorption in traditional UCNPs. This design developed a synergistic sensitization-plasmonic architecture by integrating IR-783 dye-sensitized core/shell UCNPs with aligned Au NRs, and resulted in a dramatic 120-fold enhancement in UCL intensity and elevated the quantum yield from 0.2% to 1.2%^[118]. In Figure 15a,b,c, when incorporated into the electron transport layer of PSCs, this engineered composite contributed to a notable increase in power conversion efficiency (IPCE) from 19.4% to 20.5% under standard AM 1.5 G illumination, representing the highest reported value for UC-assisted PSCs at the time. Under concentrated sunlight (1 W/cm²), the efficiency further rose to 21.1%, with mechanistic studies confirming the dominant role of enhanced UC under high photon flux. Recently, our group designed a multilayer core-shell-shell-shell (CSSS) UCNP architecture, spatially segregating Ho³⁺, Er³⁺, and Tm³⁺ ions to collectively harvest NIR light from 1,100–2,200 nm^[119]. When integrated as a film on commercial silicon solar cells, this CSSS converter delivered a record 0.87% absolute PCE gain (total 19.37%), extending the photoresponse to 2,200 nm (Figure 15d). Figure 15e,f quantifies the UC efficiency, showing a high estimated PLQY of ~5.3% under solar-relevant NIR flux, and provides direct evidence of the achieved spectral broadening, with the calculated IPCE curve confirming significant photocurrent generation out to 2,200 nm. Chouryal *et al.* designed and synthesized phase-pure, cubic BaGdF₅: Er³⁺/Yb³⁺ nanocrystals via an ionic liquid route, as an effective spectral conversion layer for dye-sensitized solar cells^[120]. When composited with the TiO₂ photoanode, the nanophosphors convert sub-bandgap NIR photons into Vis emission, which is subsequently harvested by the sensitizing dye. This integration yielded a notable 68.5% relative increase in PCE (from 4.60% to 7.75%) under 1 sun illumination (Figure 15g). Mao *et al.* reported an innovative core-shell structure NaCsWO₃@NaYF₄: Yb, Er UCNPs, which utilizing the strong LSPR of NaCsWO₃ in the NIR region to dramatically enhance the UCL of the surrounding shells by over 124-fold, creating a highly efficient spectral converter^[121]. When applied to PSCs, these nanocomposites could broaden the spectral response via plasmon-enhanced photon UC, while concurrently modifying the perovskite film morphology and passivating surface defects at the grain boundaries. This synergistic approach of spectral management and interfacial engineering led to a significant device performance enhancement, elevating the PCE from 16.01% to 18.89% (Figure 15h).

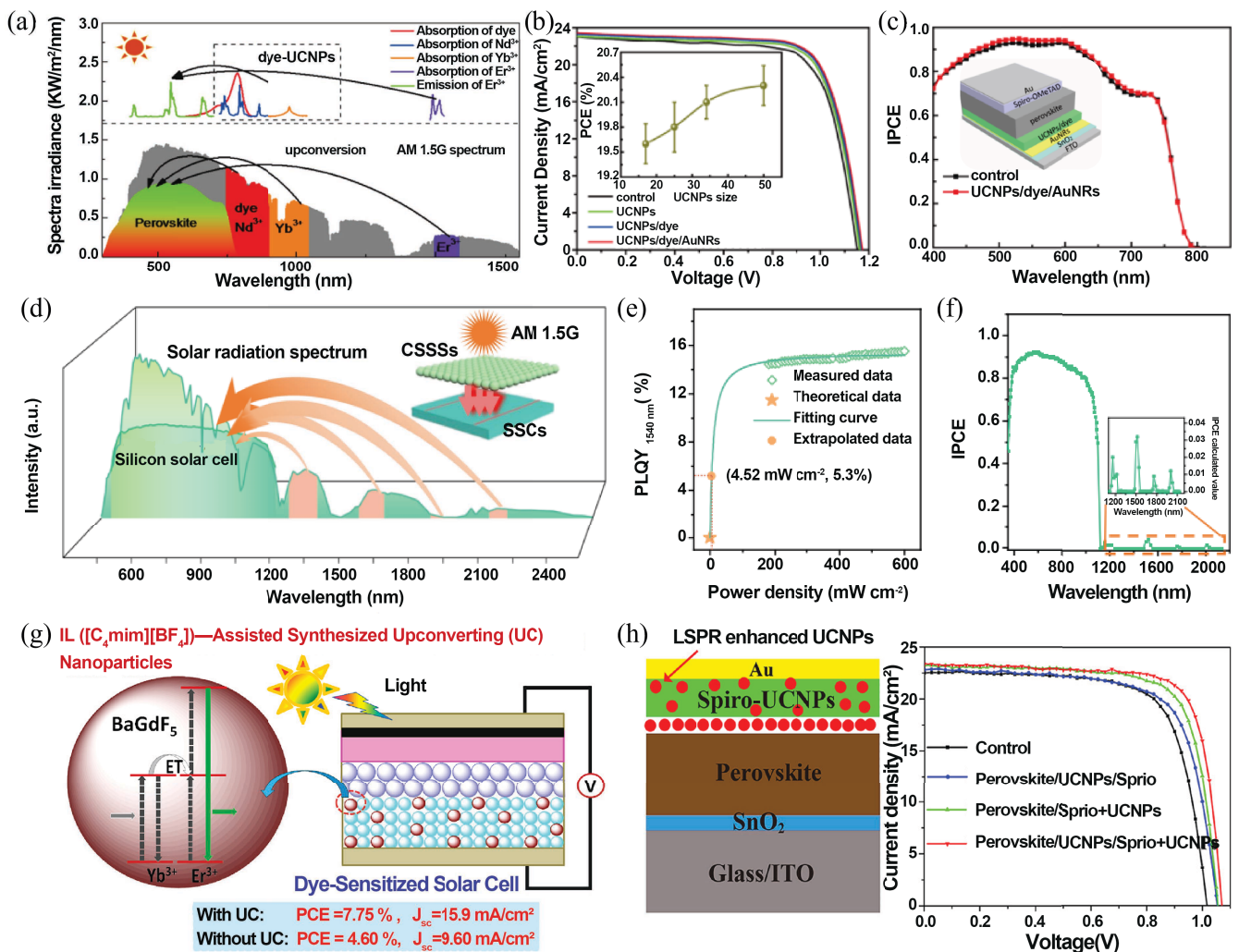


Figure 15. Optical filed modulated UCNCs-based solar cells. (a) NIR and UV to Vis photon conversion for full spectrum response PSCs; (b) Reverse J-V characteristics of PSCs based on the control film and films integrated with UCNPs, UCNPs/IR-783 dye, and UCNPs/IR-783 dye/Au NPs composites under AM 1.5 G illumination; (c) IPCE spectra of

PSCs with and without the UCNPs/IR-783 dye/Au NPs composite film. The inset is the structure of the UCNPs/IR-783 dye/Au NPs PSCs; (d) Schematic of the spectral range broadening of SSCs by CSSS, with an inset illustrating the CSSS-coated SSC under AM 1.5 G illumination; (e) UC PLQY of CSSS measured under 1,520 nm excitation at varying power densities, with extrapolated low-power PLQY; (f) IPCE spectra of CSSS-coated SSCs; inset shows the magnified response in the 1,100–2,200 nm region; (g) The structure and working mechanism diagram of dye-sensitized solar cells; (h) The structure and J - V characteristics of NaCsWO₃@NaYF₄@NaYF₄:Yb, Er UCNPs based PSCs. Republished with permission from^[118–121]. UCNPs: upconversion nanocrystals; NIR: near-infrared; UV: ultraviolet; PSCs: perovskite solar cells; UCNPs: upconversion nanoparticles; IPCE: increase in power conversion efficiency; SSCs: silicon solar cells; CSSS: core-shell-shell-shell; PLQY: photoluminescence quantum yield.

4. Conclusions and Perspectives

In recent years, significant progress has been made in the engineering of nano-/micro-structures for UCL. This review systematically elaborates on strategies to control UCL through photonic structures, including plasmonic nanostructures, dielectric superstructures, optical microcavities, and wavefront shaping devices. Key advancements are: (1) plasmonic nanostructures, which enable localized field enhancement, boosting UCL intensity by several orders of magnitude; (2) optical microcavities, where resonance regulation improves luminescence efficiency and directionality; (3) dielectric superstructures, which leverage wavefront manipulation for UCL polarization control and spatial distribution modulation; (4) dynamic platforms (e.g., LC-SLMs), which realize real-time reconfiguration of UCL properties. These strategies effectively overcome intrinsic limitations of rare-earth ion $4f$ - $4f$ transitions, opening new avenues for UCL in biological sensing and imaging, lasers, and optoelectronic devices^[122].

Despite these advances, UCL micro-/Nanostructure regulation faces considerable challenges alongside development opportunities. Several fundamental issues must be addressed to advance the field: short effective light-matter interaction distances between excitation light and artificial micro-/nanostructures, narrow excitation wavelength ranges of conventional UC processes, and the need to optimize optical field distributions to shorten radiative lifetimes and enhance UCL^[123]. A core unmet challenge lies in the perpetual trade-off between metallic field confinement/loss and dielectric Q -factor/mode volume^[124]. Future advances hinge on emerging materials (2D materials, phase-change materials, and topological insulators) and hybrid designs, integrating low-loss confinement, dynamic tuning, and multifunctional synergy to transcend single-material limitations for efficient UCL under incoherent light^[125].

Future progress will likely hinge on the synergistic, multi-scale integration of these complementary strategies, combining the nanoscale precision and high enhancement factors of resonant structures with the macroscopic adaptability of programmable optics to create hybrid systems that transcend the limitations of any single approach^[126]. Building on this core principle, future research should focus on: designing broadband, multi-resonant composite structures (notably low-loss dielectric superstructures) integrating gradient geometric engineering and dispersion tailoring for efficient UCL under incoherent light excitation (e.g., sunlight); developing low-loss composite structures with high field enhancement and integrated photonic functionalities; exploring novel functionalities enabled by precise optical-field engineering beyond enhancement factors, including UCL for quantum information (e.g., high-coherence single-photon sources, spin-photon interfaces) and neuromorphic sensing (analog signal processing via dynamically tunable UCL modulation); and translating micro-/nanostructure engineering into practical devices for biomedicine, quantum technology, and energy applications^[127]. With growing integration of materials science and nano-optics, UCL micro-/nanostructure engineering is poised to unlock broader prospects.

Declarations

Authors contribution

Ji Y: Conceptualization, writing-original draft, writing-review & editing.

Zhang T: Writing-review & editing.

Xu W, Dong B: Conceptualization, writing-review & editing.

Conflicts of interest

Bin Dong is an Editorial Board Member of *Light Manipulation and Applications*. The authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

This work was supported by the National Key Research and Development Program of China (Grant No. 2024YFA1409904), National Natural Science Foundation of China (Grant No. 12474400, No. U24A202439, No. U2441222 and No. 62575048), the Science and Technique Foundation of Liaoning Province (Grant No. 2023JH2/101700309, No. 2023JH2/101800012 and No. 2024JH3/50100028), and the Young Top Talents of Liaoning Province Xingliao Talent Plan (Grant No. XLYC2203170).

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