



Boosting photoluminescence efficiency in Yb³⁺-doped CsPbCl₃ nanocrystals via metal chloride post-treatment for high-performance luminescent solar concentrators

Tongxin Yan^{1,2}, Zixuan Liu^{1,2}, Shuaiyao Zhang^{1,2}, Lei Song^{1,2}, Sihang Ji^{1,2}, Ke Xing^{1,2}, Jialong Zhao^{3,4}, Xi Yuan^{1,2,*}

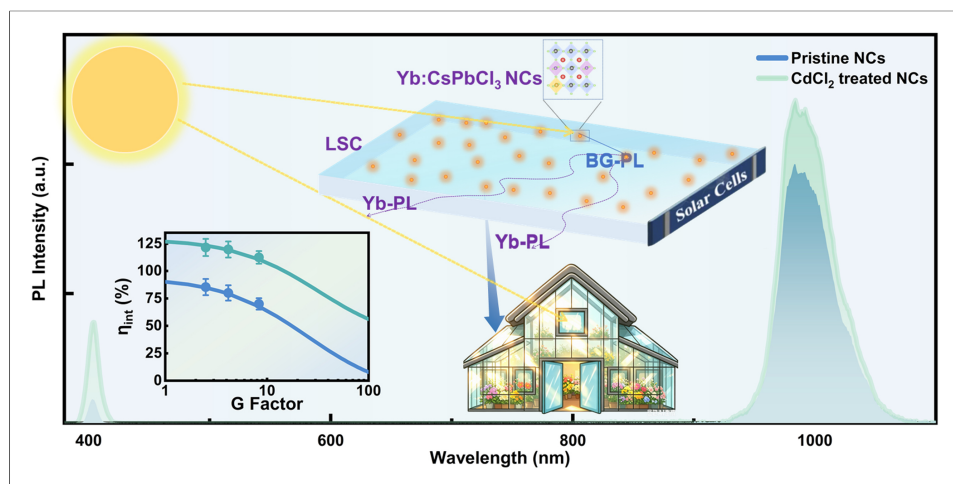
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Abstract

Yb³⁺-doped perovskite nanocrystals (NCs) featuring quantum-cutting capability exhibit enormous potential for luminescent solar concentrators (LSCs) due to their theoretically achievable 200% photoluminescence quantum yield (PLQY). However, their practical applications are still limited by defect-assisted nonradiative recombination, insufficient exciton-to-Yb³⁺ energy transfer efficiency, and poor operational stability. Herein, we demonstrate a CdCl₂ post-treatment strategy to regulate the lattice structure and photoluminescence (PL) dynamics of Yb³⁺:CsPbCl₃ NCs. As a result, the PLQY is significantly enhanced from 125.3% to 177.4%, accompanied by an increase in exciton to Yb³⁺ energy transfer efficiency from 75.9% to 86.4%. In addition, the treated NCs exhibit substantially improved photostability and thermal stability, with the thermal activation energy increasing from 61.8 ± 6.2 to 90.9 ± 2.4 meV. Compared with ZnCl₂, NiCl₂, and CuCl₂ treatments, CdCl₂ shows uniquely superior enhancement of the exciton to Yb³⁺

¹Jilin Provincial Key Laboratory of Wide Bandgap Semiconductor Material Growth and Device Applications, Key Laboratory of Functional Materials Physics and Chemistry of the Ministry of Education, Jilin Normal University, Changchun 130103, Jilin, China.

²College of Information Technology, Jilin Engineering Research Center of Optoelectronic Materials and Devices, Jilin Normal University, Siping 136000, Jilin, China.

³School of Physical Science and Technology, State Key Laboratory of Featured Metal Materials and Life-cycle Safety for Composite Structures, Guangxi University, Nanning 530004, Guangxi, China.

⁴Hebei Ledphor Optoelectronics Technology Co., Ltd., Baoding 071000, Hebei, China.

*Correspondence to: Prof. Xi Yuan, Jilin Provincial Key Laboratory of Wide Bandgap Semiconductor Material Growth and Device

Applications, Key Laboratory of Functional Materials Physics and Chemistry of the Ministry of Education, Jilin Normal University, Changchun 130103, Jilin, China. E-mail: yuanx@jlnu.edu.cn

energy transfer efficiency and Yb³⁺ emission. Flexible LSCs fabricated based on the treated NCs exhibit high visible transparency and efficient near-infrared (NIR) photon waveguiding and concentrating capability, achieving an internal optical efficiency exceeding 120% and delivering enhanced photovoltaic performance when coupled with silicon solar cells. This work provides an effective strategy for developing high-performance Yb³⁺-doped perovskite NCs and flexible transparent LSCs for building-integrated photovoltaics.

INTRODUCTION

Luminescent solar concentrators (LSCs) have emerged as a promising technology for building-integrated photovoltaics, offering a viable pathway to transform conventional windows into power-generating architectural elements^[1–10]. Lanthanide-doped perovskite nanocrystals (NCs), especially Yb³⁺-doped CsPbX₃ (X = Cl, Br, I) NCs, have emerged as highly attractive emitters for LSCs because of their strong ultraviolet absorption, solution-processability, and unique quantum-cutting properties^[11–17]. In Yb³⁺-doped perovskite NCs, one high-energy photon absorbed by the perovskite host can generate two near-infrared (NIR) photons through exciton to Yb³⁺ quantum-cutting, enabling a theoretical photoluminescence quantum yield (PLQY) limit of 200%^[14,16,18,19]. Moreover, the large Stokes shift between ultraviolet absorption and Yb³⁺ NIR emission effectively suppresses reabsorption losses and closely matches the spectral response of silicon solar cells^[20,21]. Luo *et al.* reported Yb³⁺:CsPbCl₃ NC-based LSCs with internal optical efficiencies exceeding 100%, demonstrating the considerable potential of quantum-cutting perovskites for transparent photovoltaics^[22]. More importantly, Crane and co-workers demonstrated that integrating Yb³⁺-doped quantum-cutting layers with silicon photovoltaic cells can provide substantial performance gains under real-world solar irradiance and elevated operational temperatures, highlighting the practical significance of Yb³⁺-doped perovskites for climate-resilient solar-energy harvesting^[23].

Despite these advances, the luminescence performance and operational stability of Yb³⁺:CsPbCl₃ NCs remain insufficient for practical LSC applications^[21–23]. Post-synthetic metal-halide treatments have proven effective at improving the optical properties of perovskite NCs by passivating surface defects and modulating the lattice. For example, Yong *et al.* incorporated Ni²⁺ ions into CsPbCl₃ NCs to enhance short-range structural order and eliminate vacancy defects, achieving a near-unity violet PLQY^[24]. Li *et al.* developed a post-synthetic surface trap removal strategy using a ZnX₂ hexane solution, successfully elevating the PLQYs of CsPbX₃ quantum dots up to 95% via effective halide passivation^[25]. Furthermore, Ji *et al.* achieved a pioneering near-unity red emission in Mn²⁺:CsPbCl₃ NCs through a room-temperature CdCl₂ post-treatment, demonstrating that CdCl₂ can effectively promote carrier detrapping from defect states to excitonic states and thereby enhance radiative recombination^[26]. However, the influence of metal-halide post-treatments on lanthanide-doped perovskite NCs remains insufficiently understood. In particular, because the Yb³⁺ sensitization process strongly depends on energy transfer from the exciton to Yb³⁺ and local lattice environments around dopant ions^[27], the role of post-treatment chemistry in tuning the luminescent properties of Yb³⁺-doped perovskites is expected to differ substantially from that in undoped perovskites. Therefore, developing an effective post-treatment strategy to regulate exciton emission and Yb³⁺ sensitization is crucial for achieving high-performance quantum-cutting LSC materials.

Herein, we demonstrate that CdCl₂ post-treatment provides an effective surface-lattice synergistic engineering strategy for enhancing the luminescence and stability of Yb³⁺:CsPbCl₃ NCs. After CdCl₂ post-treatment, the total PLQY of Yb³⁺:CsPbCl₃ NCs is significantly increased from 125.3% to 177.4%, accompanied by substantial improvements in photostability and thermal stability. Compared with ZnCl₂,

NiCl₂, and CuCl₂ treatments, CdCl₂ shows uniquely superior enhancement of the exciton to Yb³⁺ energy transfer efficiency and Yb³⁺ emission. Furthermore, the LSCs fabricated from treated NCs exhibit an internal optical efficiency of 121.6% and enhanced photovoltaic performance when coupled with silicon solar cells, demonstrating the potential of Yb³⁺-doped perovskite NCs for high-performance, transparent, and flexible photovoltaic applications.

EXPERIMENTAL

Synthesis of metal chloride-treated Yb³⁺:CsPbCl₃ NCs

Yb³⁺-doped CsPbCl₃ NCs were synthesized using a modified hot-injection method^[28], followed by post-treatment with different metal chlorides at room temperature. Detailed information on materials, characterization methods, and device measurements is provided in the [Supplementary Materials](#). Before NC synthesis, metal chloride ethanol solutions were prepared by dissolving 0.27 mmol of CdCl₂, ZnCl₂, NiCl₂, and CuCl₂ separately in 8 mL of anhydrous ethanol under continuous stirring until clear homogeneous solutions were obtained. The resulting solutions were stored at room temperature for subsequent post-treatment.

In a typical synthesis, Yb(OAc)₃·4H₂O (0.02 mmol), Pb(OAc)₂·3H₂O (0.20 mmol), CsOAc solution (0.28 mL, 1 mol L⁻¹, prepared by dissolving CsOAc in absolute ethanol), oleic acid (1 mL), oleylamine (0.5 mL), and 1-octadecene (5 mL) were loaded into a 50 mL three-neck flask. The mixture was vacuum-degassed at 120 °C for 30 min. Subsequently, the system was heated to 240 °C under an argon atmosphere, followed by the rapid injection of a precursor solution consisting of trimethylsilyl chloride (TMS-Cl) (0.2 mL) and 1-octadecene (ODE) (0.5 mL). Immediately after injection, the reaction was quenched using an ice-water bath.

The crude product was purified by centrifugation at 5,000 rpm for 10 min. The precipitate was collected, redispersed in hexane, and centrifuged again at 5,000 rpm for 10 min. The supernatant containing purified Yb³⁺:CsPbCl₃ NCs was collected for further use. For post-treatment, 0.5 mL of the purified NC solution was mixed with a desired amount of metal chloride ethanol solution, and the mixture was stirred at room temperature for 20 min to obtain metal-chloride-treated Yb³⁺:CsPbCl₃ NCs.

Fabrication of Yb³⁺:CsPbCl₃ NC-LSCs

Flexible LSCs were fabricated by embedding the synthesized NCs into a polydimethylsiloxane (PDMS) matrix. Typically, 1 mL of NC solution was mixed with 3 g of PDMS and 0.4 g of curing agent and magnetically stirred at 600 rpm for 30 min at room temperature to obtain a homogeneous mixture. The mixture was subsequently poured into a mold and cured in a vacuum oven at 50 °C for 2 h, yielding flexible Yb³⁺:CsPbCl₃ NC-based LSCs.

RESULTS AND DISCUSSION

[Figure 1](#) presents the optical, crystallographic, morphological, and surface chemical characterizations of untreated and CdCl₂ post-treated Yb³⁺-doped CsPbCl₃ NCs. As shown in [Figure 1A](#), the untreated Yb³⁺:CsPbCl₃ NCs exhibit a distinct absorption peak at 398 nm, corresponding to the first excitonic absorption peak of the CsPbCl₃ host^[14,19,29,30]. The photoluminescence (PL) spectrum displays two characteristic emission bands, a narrow blue emission centered at 405 nm, assigned to the band-edge (BG) recombination of the CsPbCl₃ host, and a NIR emission centered at 985 nm, originating from the characteristic ²F_{5/2} → ²F_{7/2} transition of doped Yb³⁺ ions^[16,21,23,29]. After CdCl₂ post-treatment, the excitonic absorption peak slightly blue-shifts from 398 to 397 nm, while the host band-edge emission shifts from 405 to 404 nm [[Figure 1B](#)]. In contrast, the Yb³⁺-related NIR emission remains centered at 985 nm, indicating that the local crystal-field variation induced by CdCl₂ treatment has a negligible influence on the energy level

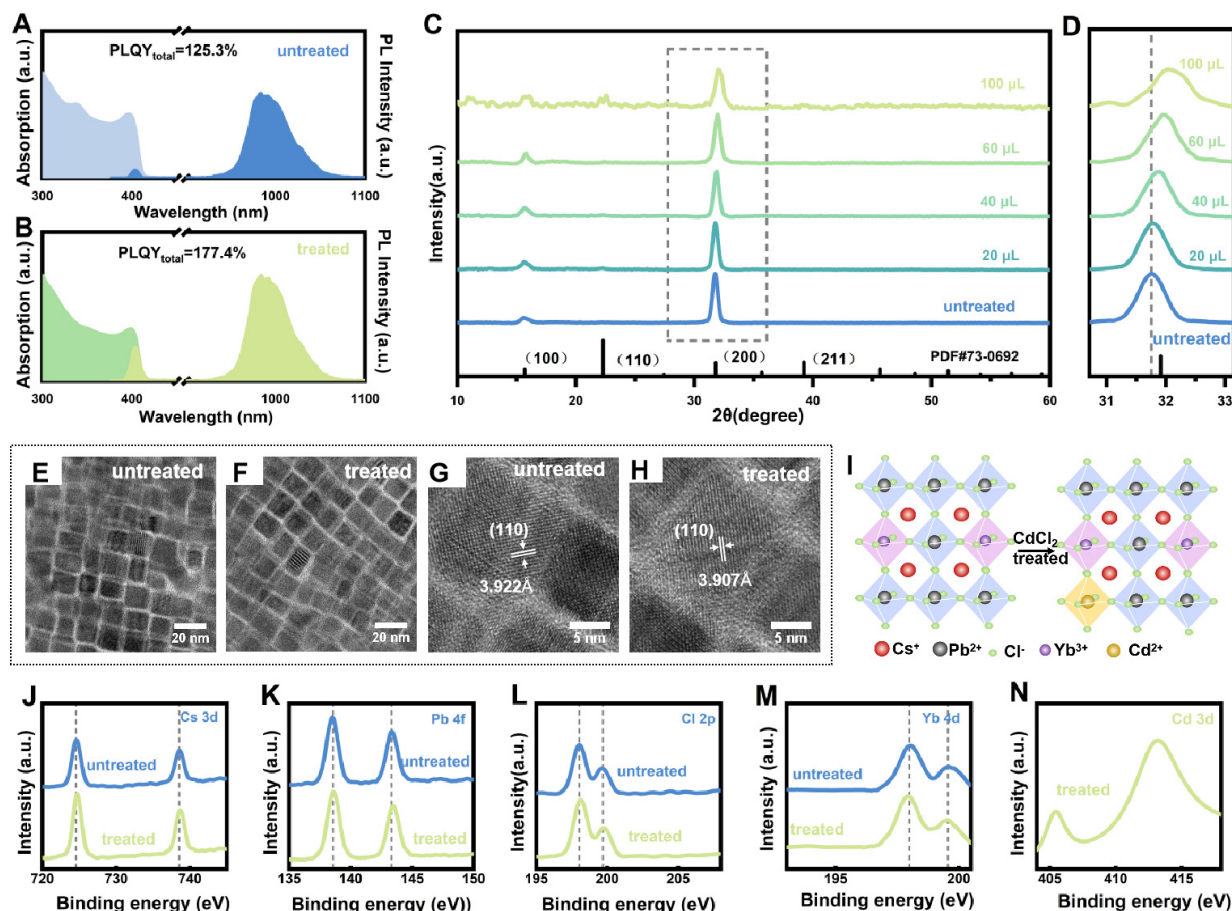


Figure 1. (A and B) UV-vis absorption and PL spectra of Yb³⁺:CsPbCl₃ NCs before and after CdCl₂ post-treatment; (C and D) XRD patterns of Yb³⁺:CsPbCl₃ NCs treated with different amounts of CdCl₂, together with an enlarged view around the (200) diffraction peak at approximately 31.8°. The standard XRD pattern (PDF#73-0692) of cubic CsPbCl₃ is shown at the bottom as a reference; (E-H) TEM images of Yb³⁺-doped CsPbCl₃ NCs before and after CdCl₂ post-treatment (scale bar: 20 nm), along with the corresponding high-resolution TEM images (scale bar: 5 nm); (I) Schematic illustration of the lattice of Yb³⁺-doped CsPbCl₃ NCs before and after CdCl₂ post-treatment; (J-N) High-resolution XPS spectra of untreated (blue) and CdCl₂ post-treated (green) Yb³⁺:CsPbCl₃ NCs, including Cs 3d, Pb 4f, Cl 2p, Yb 4d, and Cd 3d regions. XRD: X-ray diffraction; NCs: nanocrystals; TEM: transmission electron microscopy; XPS: X-ray photoelectron spectroscopy; PLQY: photoluminescence quantum yield; UV-vis: ultraviolet-visible; PL: photoluminescence.

splitting of Yb³⁺ 4f states. Notably, CdCl₂ post-treatment significantly enhances the luminescence intensity of the Yb³⁺:CsPbCl₃ NCs, with the total PLQY (including excitonic and Yb³⁺ emission) increasing from 125.3% to 177.4%. The PLQY exceeding 100% suggests that the Yb³⁺ emission is associated with an efficient quantum-cutting process, in which one high-energy excitation absorbed by the CsPbCl₃ host can generate more than one NIR photon through Yb³⁺ sensitization^[31–33].

Figure 1C shows the X-ray diffraction (XRD) patterns of these Yb³⁺-doped CsPbCl₃ NCs; they retain the structures of the parent cubic CsPbCl₃ (PDF#73-0692). The NCs exhibit two distinct diffraction peaks at 15.7° and 31.8°, which can be indexed to the (100) and (200) crystal planes, respectively, indicating a (100) preferred orientation^[30]. Importantly, no additional impurity peaks are detected after CdCl₂ treatment, suggesting that the post-treatment does not induce secondary crystalline phases such as Cd-containing salts or lead-deficient by-products. However, with increasing CdCl₂ addition, the diffraction peaks shift gradually to higher angles [Figure 1D], and Rietveld refinement confirms the slight contraction of the average lattice parameters after CdCl₂ treatment [Supplementary Figure 1].

Transmission electron microscopy (TEM) further confirms that CdCl_2 post-treatment preserves the morphology of the $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs. As shown in [Figure 1E and F](#), both untreated and CdCl_2 -post-treated NCs exhibit uniform and well-dispersed cubic morphologies. The corresponding particle-size distributions [[Supplementary Figure 2](#)] show that the average particle size decreases slightly from 14.5 ± 2.5 nm to 13.6 ± 2.3 nm after CdCl_2 post-treatment. This moderate size reduction is consistent with the slight blue shift observed in both the absorption and host PL spectra, suggesting that CdCl_2 treatment may induce slight surface etching. High-resolution TEM images [[Figure 1G and H](#)] display clear lattice fringes, confirming the high crystallinity of both NCs. The lattice spacing assigned to the (110) planes decreases from 3.922 Å for untreated NCs to 3.907 Å after CdCl_2 treatment. This reduction agrees well with the XRD peak shift toward higher diffraction angles and provides additional evidence for CdCl_2 -induced lattice contraction. A schematic illustration of the proposed lattice evolution before and after CdCl_2 post-treatment is shown in [Figure 1I](#).

X-ray photoelectron spectroscopy (XPS) was conducted to investigate the surface chemical states and elemental composition of the NCs. As shown in [Figure 1J–N](#), the characteristic signals of Cs, Pb, Cl, and Yb are clearly observed in the untreated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs, confirming the successful introduction of Yb^{3+} into the CsPbCl_3 NCs. After CdCl_2 post-treatment, an additional Cd signal appears, verifying the presence of Cd in the treated NCs. Meanwhile, the Cs 3d, Pb 4f, and Cl 2p peaks exhibit slight shifts toward higher binding energies, suggesting strengthened Pb–Cl interactions in the NCs, consistent with previous reports^[29]. To further examine the elemental composition after CdCl_2 treatment, the Yb and Cd contents of the NCs were determined by Energy Dispersive X-ray Spectroscopy (EDS) [[Supplementary Table 1](#)]. The Yb elemental content remains nearly constant at 1.72%–1.76%, whereas the Cd content progressively increases from 2.93% to 8.57% with increasing CdCl_2 amount. These results indicate that Cd incorporation does not appreciably alter the Yb content under the present treatment conditions, allowing the effects of CdCl_2 treatment to be evaluated at an essentially constant Yb doping level.

To further elucidate the role of CdCl_2 post-treatment in regulating the photophysical properties of $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs, steady-state and time-resolved PL measurements were performed. As shown in [Figure 2A](#), the PL intensities of the CsPbCl_3 host (~ 405 nm) and Yb^{3+} emission (985 nm) are strongly dependent on the amount of CdCl_2 used during post-treatment. When the CdCl_2 amount is increased from 0 to 60 μL , the band-edge excitonic emission shows a 5.6-fold enhancement, and the NIR emission of Yb^{3+} exhibits a 1.35-fold increase relative to that of untreated NCs. The more pronounced enhancement of the host emission suggests that CdCl_2 treatment effectively suppresses nonradiative recombination associated with surface defects^[25,26]. Meanwhile, the increase in Yb^{3+} emission indicates that the improved host lattice environment also enhances the sensitization of Yb^{3+} centers^[27]. However, when the CdCl_2 amount is further increased to 100 μL , the excitonic and Yb^{3+} emissions show a slight decrease, suggesting that excessive CdCl_2 treatment introduces additional structural defects that partially offset the benefits of defect passivation.

The carrier recombination dynamics were then investigated by time-resolved PL spectroscopy. [Figure 2B](#) shows the band-edge PL decay curves of $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs treated with different amounts of CdCl_2 . The untreated NCs exhibited a biexponential decay behavior, consisting of a fast component associated with intrinsic excitonic recombination and a slower component arising from defect-related localized states or self-trapped excitons^[14]. With increasing CdCl_2 content, the decay gradually evolved from multiexponential to nearly single-exponential, indicating that the long-lived defect-related component was effectively suppressed. [Figure 2C](#) presents the corresponding Yb^{3+} decay curves, which become progressively slower with increasing CdCl_2 treatment, indicating reduced nonradiative defects and a more favorable local environment around the Yb^{3+} centers. The decay curves were fitted using biexponential functions, and the average PL lifetimes are summarized in [Supplementary Tables 2 and 3](#) and plotted in [Figure 2D](#). The average Yb^{3+} lifetime increases

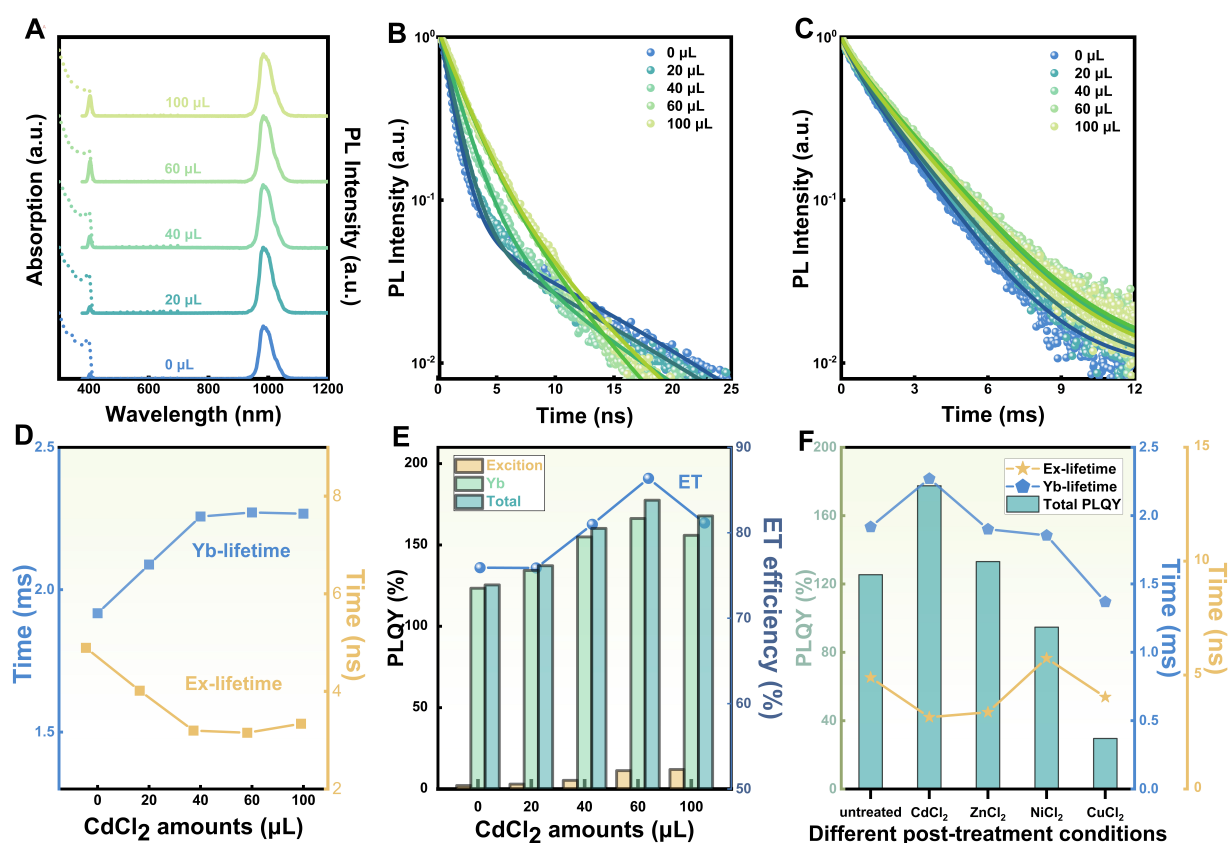


Figure 2. (A) Absorption and PL spectra of Yb³⁺:CsPbCl₃ NCs post-treated with different amounts of CdCl₂. Time-resolved PL decay curves of the excitons (B) and Yb³⁺ emissions (C), respectively; (D) Average PL lifetimes of the excitons and Yb³⁺ ions extracted from biexponential fitting; (E) PLQYs of the excitonic emission, Yb³⁺ near-infrared emission, and total emission, together with the exciton to Yb³⁺ energy transfer efficiencies (η_{ET}), for Yb³⁺:CsPbCl₃ NCs treated with different amounts of CdCl₂; (F) Comparison of the average PL lifetimes of the excitons and Yb³⁺ ions, as well as the total PLQYs of Yb³⁺:CsPbCl₃ NCs treated with different metal chlorides (CdCl₂, ZnCl₂, NiCl₂, and CuCl₂). PLQY: Photoluminescence quantum yield; NCs: nanocrystals; PL: photoluminescence.

from 1.92 ms for the untreated NCs to 2.27 ms at 60 μL CdCl₂ and remains essentially unchanged at higher CdCl₂ loading. In contrast, the average exciton lifetime decreases from 4.90 ns to 3.15 ns as the CdCl₂ amount increases from 0 to 60 μL , reflecting the efficient removal of long-lived defect-related recombination channels. When the CdCl₂ amount is further increased to 100 μL , the exciton lifetime slightly increases to 3.34 ns, suggesting that excess CdCl₂ introduces new defect/trap states. The shortening of the host exciton lifetime and prolongation of the Yb³⁺ lifetime indicate that CdCl₂ post-treatment not only suppresses defect/trap-assisted recombination but also promotes more efficient exciton funneling to Yb³⁺ centers.

The PLQY and exciton to Yb³⁺ energy transfer efficiency are summarized in Figure 2E. With increasing CdCl₂ content, the PLQY of the host excitonic emission rose from 2.0% to 11.9%, confirming a substantial enhancement in band-edge radiative recombination. The Yb³⁺ PLQY increases from 123.3% to a maximum of 166.2% at 60 μL CdCl₂, before decreasing slightly to 155.8% at 100 μL . As a result, the total PLQY rises from 125.3% for the untreated NCs to 177.4% at the optimal CdCl₂ amount. In general, the PLQY of Yb³⁺ emission in Yb³⁺:CsPbCl₃ NCs is determined by the exciton-to-Yb³⁺ energy-transfer efficiency (η_{ET}) and the intrinsic radiative efficiency of the Yb³⁺ ions (η_{Yb})^[33,34]. Because one quantum-cutting event can generate two NIR photons, the experimentally measured Yb³⁺ PLQY is twice the effective Yb³⁺ NIR emission efficiency (QY_{NIR}). Accordingly, QY_{NIR} can be expressed as follows^[33,34]:

$$QY_{\text{NIR}} = \eta_{\text{ET}} \times \eta_{\text{Yb}} \quad (1)$$

$$\eta_{\text{ET}} = \frac{nk_{\text{ET}}}{k_{\text{BG-r}} + k_{\text{BG-nr}} + nk_{\text{ET}}} \quad (2)$$

$$\eta_{\text{Yb}} = \frac{k_{\text{Yb-r}}}{k_{\text{Yb-r}} + k_{\text{Yb-nr}}} \quad (3)$$

$$\tau_{\text{Yb}} = \frac{1}{k_{\text{Yb-r}} + k_{\text{Yb-nr}}} \quad (4)$$

Here, k_{ET} is the exciton-to- Yb^{3+} energy-transfer rate constant, n is the number of optically active Yb^{3+} ions, and $k_{\text{BG-r}}$ and $k_{\text{BG-nr}}$ are the radiative and nonradiative recombination rate constants of the band-edge excitons, respectively. $k_{\text{Yb-r}}$ and $k_{\text{Yb-nr}}$ denote the radiative and nonradiative decay rate constants of the Yb^{3+} excited state, respectively, while τ_{Yb} is the Yb^{3+} PL lifetime. Because these decay rates are sensitive to the local lattice environment surrounding the Yb^{3+} centers, the Yb^{3+} PL lifetime can be used to evaluate the intrinsic radiative efficiency of Yb^{3+} . Thus, the exciton-to- Yb^{3+} energy-transfer efficiency can be estimated from the measured Yb^{3+} PLQY and PL lifetime. The η_{ET} increases from 75.9% to 86.4% as the CdCl_2 amount increases to 60 μL , and then decreases to 81% at 100 μL , as seen in Figure 2E. CdCl_2 treatment increases the exciton-to- Yb^{3+} energy-transfer efficiency and simultaneously prolongs the Yb^{3+} lifetime to 2.27 ms, indicating more efficient population of the Yb^{3+} excited state together with reduced nonradiative decay of Yb^{3+} , thereby contributing to the enhanced Yb^{3+} emission and PLQY. Transient absorption (TA) measurements were performed on the untreated and CdCl_2 -treated NCs to investigate their excited-state carrier dynamics [Supplementary Figure 3]. The average numbers of excitons generated per NC were estimated to be 0.081 and 0.077, respectively. Both values are well below 0.2, confirming that the measurements were conducted in the single-exciton regime^[33,35]. Detailed calculations of the average exciton number are provided in the Supporting Information. Unlike undoped CsPbCl_3 NCs, in which defect passivation primarily enhances host radiative recombination, $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs involve an additional exciton-to- Yb^{3+} energy-transfer pathway. Consequently, exciton-to- Yb^{3+} energy transfer directly competes with defect-assisted nonradiative recombination. Photoexcited excitons can be trapped by halide vacancies and localized defect states, resulting in long-lived defect-related recombination and substantial energy dissipation before energy transfer to Yb^{3+} occurs. CdCl_2 treatment may modify the local lattice environment through Cd^{2+} , while the introduced Cl^- ions can passivate halide-vacancy-related defects^[26,36]. As a result, the defect-assisted nonradiative decay channels are significantly suppressed, allowing a larger fraction of excitons to undergo energy transfer to Yb^{3+} . To more clearly illustrate the relationship between exciton decay dynamics and energy-transfer efficiency, η_{ET} and the average exciton lifetime are plotted as functions of the CdCl_2 amount in Supplementary Figure 4. As the CdCl_2 amount increases from 0 to 60 μL , the average exciton lifetime decreases from 4.90 to 3.15 ns, while η_{ET} simultaneously increases, which is consistent with the PLQY evolution discussed above.

To evaluate whether this enhancement is specific to CdCl_2 , other metal chlorides, including ZnCl_2 , NiCl_2 , and CuCl_2 , were also used for post-treatment under similar conditions. Previous studies have reported that post-treatment with metal chlorides such as CuCl_2 can improve the luminescence properties of undoped CsPbCl_3 NCs by alleviating PbCl_6 octahedral distortion through Cu^{2+} incorporation and passivating surface defects with additional Cl^- ions^[36]. However, in Yb^{3+} -doped perovskite NCs, where the overall emission efficiency depends not only on defect passivation but also on the exciton to Yb^{3+} energy transfer process, the effects of these metal chlorides differ substantially.

Figure 2F compares the average lifetimes of the excitonic and Yb^{3+} emissions as well as the total PLQYs of untreated and metal-chloride-treated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs. The detailed amount-dependent results for ZnCl_2 , NiCl_2 , and CuCl_2 are provided in Supplementary Figures 5–9. Among all treatments, CdCl_2 produced the longest Yb^{3+} lifetime (2.27 ms), the shortest exciton lifetime (3.15 ns), and the highest total PLQY (177.4%).

In contrast, ZnCl_2 led to only a modest increase in total PLQY to 133%, accompanied by a moderate increase in energy-transfer efficiency and a shortened exciton lifetime [Supplementary Figures 5-7A], while the Yb^{3+} lifetime remains nearly unchanged [Supplementary Figures 8-9A]. These results suggest that ZnCl_2 mainly passivates surface defects without significantly improving the local lattice environment surrounding Yb^{3+} ions. NiCl_2 increases the host excitonic emission while progressively decreasing the Yb^{3+} emission and η_{ET} [Supplementary Figures 5-6B], indicating that the introduced Ni^{2+} ions suppress both exciton to Yb^{3+} energy transfer efficiency and Yb^{3+} -related sensitization. CuCl_2 continuously quenches both excitonic and Yb^{3+} emissions, and causes substantial reductions in Yb^{3+} lifetime and η_{ET} [Supplementary Figures 6C and 9C]. This demonstrates that the incorporated Cu^{2+} introduces severe nonradiative recombination centers in $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs, and does not give rise to the luminescence enhancement effect observed in undoped CsPbCl_3 NCs^[36]. Overall, the markedly different optical responses to ZnCl_2 , NiCl_2 , CuCl_2 , and CdCl_2 indicate that the luminescence enhancement is closely related to the nature of the metal cation rather than arising solely from the Cl component.

To further understand the structural origin of the distinct optical responses induced by different metal chlorides, the XRD patterns of the treated samples were compared. After CdCl_2 , NiCl_2 , and CuCl_2 treatment, the (200) diffraction peak shifts toward higher angles [Supplementary Figure 10], suggesting lattice contraction associated with the incorporation of smaller metal ions. In contrast, the essentially unchanged peak position after ZnCl_2 treatment suggests a relatively limited degree of Zn^{2+} incorporation into the host lattice under the present treatment conditions. The distinct effect of CdCl_2 may be related to the relatively small ionic-radius difference between Cd^{2+} and Pb^{2+} , which may help limit local structural perturbation associated with Cd-related lattice modulation^[37]. In addition, the closed-shell d^{10} electronic configuration of Cd^{2+} is less likely to introduce additional electronic states associated with partially filled d orbitals. These characteristics may contribute to the superior optical performance of the CdCl_2 -treated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs.

To evaluate the effects of CdCl_2 post-treatment on the photostability of $\text{Yb}^{3+}:\text{CsPbCl}_3$ NC films (without any encapsulation), time-dependent PL spectra were collected under continuous ultraviolet (UV) illumination. As shown in Figure 3A, the untreated NC film underwent pronounced photodegradation during 5 days of UV exposure. The peak intensity of the Yb^{3+} emission at 985 nm drops to 58% of its initial value, and the excitonic emission at 405 nm is almost entirely quenched. This rapid degradation indicates that the untreated NC film suffers from severe photoinduced defect formation and surface ligand detachment, which accelerates nonradiative recombination within the CsPbCl_3 host and weakens the host to Yb^{3+} sensitization process^[14]. In contrast, the CdCl_2 -treated NC film exhibits substantially improved resistance to photoinduced degradation [Figure 3B]. After 5 days of UV irradiation, the Yb^{3+} emission retains 90% of its initial intensity, and the excitonic emission remains essentially unchanged. This improvement can be attributed to the passivation of surface defects by Cl^- and the stabilization of the local lattice by Cd^{2+} ^[26], which together inhibit defect-state formation under UV illumination and preserve both host exciton recombination and Yb^{3+} sensitized emission. The evolution of the integrated total PL intensity as a function of irradiation time is summarized in Figure 3C. After 5 days of UV exposure, the untreated film retains only 56% of its initial emission intensity, whereas the CdCl_2 -treated film retains 91%. These results demonstrate that CdCl_2 post-treatment significantly enhances the intrinsic photostability of $\text{Yb}^{3+}:\text{CsPbCl}_3$ NC films, even in the absence of encapsulation.

The temperature-dependent PL of pristine and CdCl_2 -treated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs was further examined over the temperature range of 80-360 K, as shown in Figure 3D and E. At 80 K, the Yb^{3+} near-infrared emission exhibits well-resolved splitting with distinct sub-peaks centered at approximately 975, 1,008, and 1,035 nm.

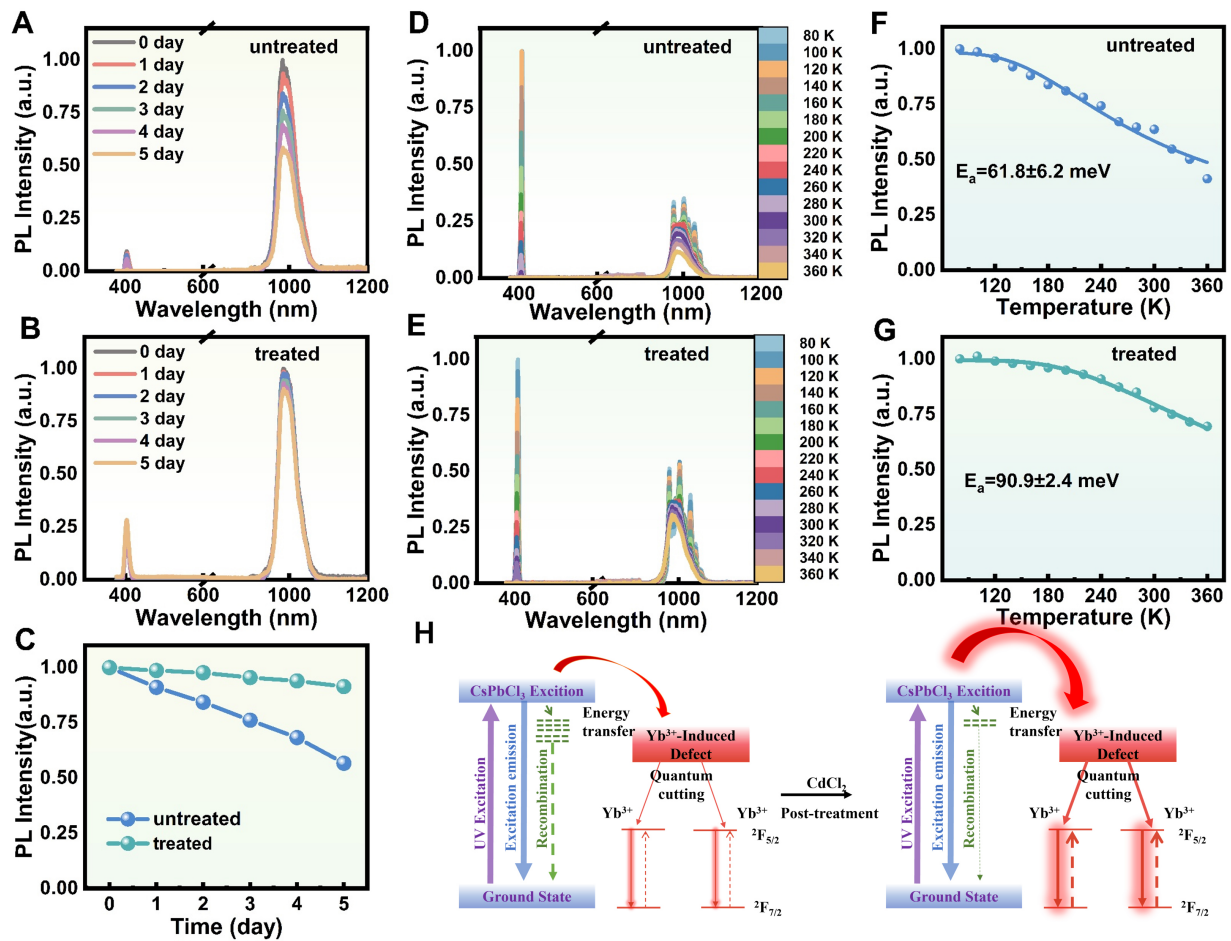


Figure 3. (A–C) PL spectra of untreated and CdCl₂-treated Yb³⁺:CsPbCl₃ NC films without encapsulation under continuous UV irradiation for different durations, along with the evolution of integrated total PL intensity versus irradiation time (normalized to unirradiated intensity); (D and E) Temperature-dependent PL spectra of untreated and CdCl₂-treated Yb³⁺:CsPbCl₃ NC films measured over the temperature range of 80–360 K; (F and G) Temperature-dependent integrated PL intensities of the Yb³⁺ emission, normalized to the emission intensity at 80 K; The solid lines represent fits to the Arrhenius equation; (H) Schematic illustration of the emission mechanism in Yb³⁺:CsPbCl₃ NCs before and after CdCl₂ treatment. PL: Photoluminescence; NC: nanocrystal; UV: ultraviolet.

As the temperature increases, these peaks gradually broaden and merge into a single asymmetric emission band due to thermal population redistribution and phonon-assisted broadening. The integrated PL intensities of Yb³⁺ emissions are summarized in Figure 3F and G. For the untreated NCs, the Yb³⁺ emission decreases monotonically with increasing temperature, showing a 59% intensity loss at 360 K relative to 80 K. In contrast, the CdCl₂-treated NCs exhibit significantly improved thermal stability. The Yb³⁺ integrated intensity decreases much more weakly with increasing temperature, and the PL thermal quenching is limited to only 31% at 360 K. Further, to quantify the thermal stability of the Yb³⁺ emission, the temperature-dependent integrated intensities were analyzed using the Arrhenius equation^[38]:

$$I(T) = \frac{I_0}{\left(1 + A \exp\left(\frac{-E_a}{k_B T}\right)\right)} \quad (5)$$

where I_0 is the initial PL intensity, $I(T)$ is the integrated PL intensity at temperature T , E_a is the activation energy for thermal quenching, k_B is the Boltzmann constant, and A is a constant related to the host material. As shown by the solid lines in Figure 3F and G, the fitted curves agree well with the experimental data, indicating that the reduction in PL intensity is mainly dominated by thermally activated carrier escape. The untreated NCs exhibit a thermal-quenching activation energy (E_a) of 61.8 ± 6.2 meV, consistent with

previous reports^[38], whereas E_a increases significantly to 90.9 ± 2.4 meV after CdCl_2 treatment. The higher E_a indicates that carriers must overcome a larger energy barrier to undergo thermal escape or to enter nonradiative decay pathways, thereby accounting for the reduced thermal quenching and improved thermal luminescence stability of the treated NCs. The proposed PL mechanism before and after CdCl_2 treatment is schematically illustrated in [Figure 3H](#). In the pristine $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs, photogenerated excitons can be trapped by defects or undergo nonradiative recombination, reducing the efficiency of exciton transfer to Yb^{3+} ions. After CdCl_2 post-treatment, excitons are more efficiently funneled through shallow Yb^{3+} -related sensitization states to the $\text{Yb}^{3+} {}^2\text{F}_{5/2}$ excited state, followed by the characteristic ${}^2\text{F}_{5/2} \rightarrow {}^2\text{F}_{7/2}$ emission at 985 nm.

The practical feasibility of the synthesized $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs for large-area, flexible LSCs was demonstrated, as seen in [Figure 4](#). As schematically illustrated in [Figure 4A](#), the Yb^{3+} -doped NCs were uniformly encapsulated into a PDMS matrix to construct the luminescent waveguide layer. Driven by the refractive index contrast at the PDMS/air interface, the isotropically emitted Yb^{3+} NIR photons were efficiently trapped via total internal reflection and guided to the edges for harvesting by the coupled silicon photovoltaic cells. The practical appearance of the NC-LSC is shown in [Figure 4B](#). Under natural daylight, the NC-LSC remains highly transparent, allowing clear visualization of the white petals, yellow stamens, and green leaves, demonstrating excellent visible-light transmittance, a desirable property for building-integrated photovoltaic windows. [Supplementary Figure 11](#) shows that CdCl_2 -treated NC-LSCs absorb primarily in the ultraviolet-blue region and are nearly transparent at the 985 nm emission of Yb^{3+} , avoiding reabsorption-induced optical efficiency loss. To visually verify the optical waveguiding capability, an infrared camera was utilized to capture the emission profile under 365 nm UV excitation [[Figure 4C](#)]. A bright, concentrated NIR emission localized at the substrate edges was observed, directly confirming that the Yb^{3+} NIR photons are efficiently waveguided to the device edges. The PDMS-based LSCs also exhibit excellent mechanical flexibility, indicating strong potential for integration into flexible and smart optical windows. Crucially, the PL spectra of the NC solution and the corresponding LSC are nearly identical [[Figure 4D](#)], indicating their homogeneous solid-solution nature^[21]. Compared with untreated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NCs at the same loading (0.60 wt.%), the CdCl_2 -treated NC-LSC exhibits a lower optical density and a weaker absorption tail in the long-wavelength region, as shown in [Supplementary Figure 12A](#), indicating that CdCl_2 effectively suppresses NC aggregation in PDMS and the associated light scattering. Consequently, the visible transmittance is improved, and the parasitic optical losses are minimized, leading to a 30.5% enhancement in LSC emission intensity [[Supplementary Figure 12B and C](#)].

The performance of the as-prepared NC-LSCs was calculated using an integrating sphere method [[Supplementary Materials](#)]. The internal optical efficiency (η_{int}) and external optical efficiency (η_{ext}) of untreated and CdCl_2 -treated NC-LSCs with different geometric gain factors (G-factors) are shown in [Figure 4E and F](#). At all device sizes, the CdCl_2 -treated NC-LSCs exhibit substantially higher efficiencies. For example, at $G = 2.5$, η_{ext} increases from 4.5% to 6.4%, while η_{int} rises from 85.4% to 121.6%, respectively. Notably, the η_{int} value exceeding 100% directly reflects the efficient quantum-cutting process. Using a previously established scaling law [[Supplementary Materials](#)], the η_{int} and η_{ext} of LSC with larger sizes can be projected. Notably, CdCl_2 treatment enables more substantial optical efficiency enhancement for LSCs with larger sizes. The CdCl_2 -treated NC-LSCs consistently outperformed the untreated ones. These improvements originate from the combination of higher Yb^{3+} PLQY, more efficient exciton to Yb^{3+} energy transfer, and reduced scattering losses afforded by CdCl_2 post-treatment. [Supplementary Table 4](#) further benchmarks the LSCs developed in this work against previously reported perovskite-based LSCs. The CdCl_2 -treated $\text{Yb}^{3+}:\text{CsPbCl}_3$ NC-LSCs exhibited competitive comprehensive performance. The present devices combine a high total PLQY of 177.4%, an exciton-to- Yb^{3+} energy-transfer efficiency of 86.4%, excellent visible transparency, efficient NIR photon waveguiding, and an internal optical efficiency of 121.6%. Together with their improved photostability and thermal stability, these characteristics highlight the potential of CdCl_2

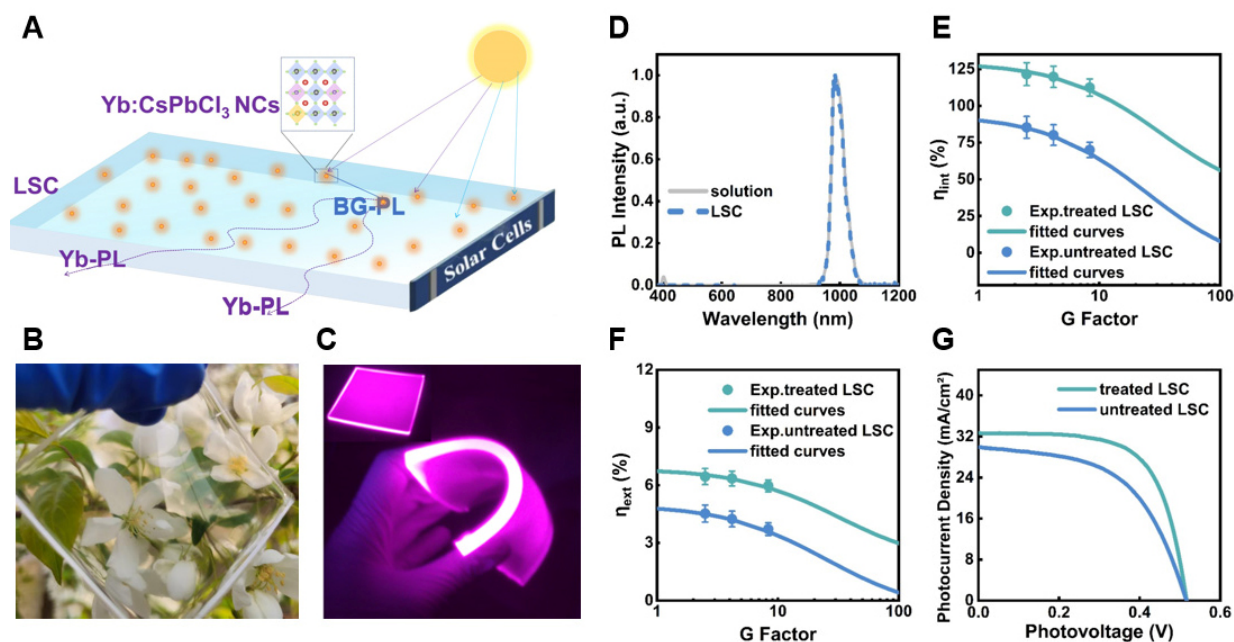


Figure 4. (A) Schematic illustration of the LSC integrated with a silicon solar cell; (B) Photograph of an LSC based on Yb³⁺-doped CsPbCl₃ NCs under sunlight (dimension: 5 cm × 5 cm × 0.3 cm); (C) Photograph of the LSC captured by a near-infrared camera under ultraviolet light (365 nm) illumination. Photographs in Figure 4B and C were taken by the authors; (D) PL spectra of the CdCl₂-treated Yb³⁺:CsPbCl₃ NC solution and the corresponding LSC; (E and F) Internal optical efficiency (E) and external optical efficiency (F) of Yb³⁺:CsPbCl₃ NC-LSCs before and after CdCl₂ post-treatment. Error bars in (E and F) represent the standard deviation from three independently fabricated LSCs; (G) J-V curves of the silicon photovoltaic cells integrated with untreated and CdCl₂-treated NC-LSCs. LSCs: Luminescent solar concentrators; NCs: nanocrystals; J-V: current density-voltage; PL: photoluminescence; BG: band gap.

-treated Yb³⁺:CsPbCl₃ NCs as high-performance emitters for flexible and transparent building-integrated photovoltaic systems. The optimized NC-LSCs were integrated with silicon photovoltaic cells and tested under standard AM 1.5G illumination. The resulting current density-voltage (J-V) and power-voltage (P-V) characteristics are depicted in Figure 4G and Supplementary Figures 13–14, with the corresponding photovoltaic parameters summarized in Supplementary Table 5. A clear enhancement in integrated device performance was observed for the CdCl₂-treated NC-LSC compared to the untreated one, directly corroborating the upgraded optical efficiency shown in Figure 4E and F. These findings demonstrate that the CdCl₂ post-treatment boosts NC emission efficiency and alleviates waveguided photon loss, ultimately yielding superior optical and photovoltaic performance in flexible Yb³⁺:CsPbCl₃ NC-LSCs.

CONCLUSIONS

In summary, this work systematically investigated the effect of post-synthetic metal chloride treatment on the luminescent properties and device performance of Yb³⁺:CsPbCl₃ NCs and their derived flexible LSCs. CdCl₂ post-treatment substantially boosts the PLQY of Yb³⁺:CsPbCl₃ NCs from 125.3% to 177.4%, accompanied by an obvious increase in the excitons to Yb³⁺ energy transfer efficiency from 75.9% to 86.4%. Compared with other common metal chloride treatments (ZnCl₂, NiCl₂, and CuCl₂), CdCl₂-treated Yb³⁺:CsPbCl₃ NCs deliver the longest Yb³⁺ PL lifetime of 2.27 ms, the highest energy transfer efficiency and PLQY, verifying its unique superiority in promoting Yb³⁺ NIR emission. The treated NCs also exhibit markedly improved photostability and thermal stability, with reduced thermal quenching and increased activation energy for carrier escape. Flexible LSCs fabricated with the optimized CdCl₂-treated Yb³⁺:CsPbCl₃ NCs show excellent waveguiding and concentrating capability for NIR photons, achieving an internal optical

efficiency exceeding 120%. This work demonstrates that CdCl_2 post-treatment is a facile and effective strategy for constructing high-performance Yb^{3+} -doped perovskite NCs, providing a promising emitting material for developing flexible, transparent LSCs for building-integrated photovoltaic applications.

DECLARATIONS

Authors' contributions

Conceived the idea, conducted the majority of the experiments, performed data analysis, and wrote the manuscript: Yan, T.; Liu, Z.; Yuan, X.

Performed device testing and characterization: Liu, Z.; Zhang, S.

Assisted in experimental work and data interpretation: Song, L.; Ji, S.; Xing, K.

Writing - review and editing, supervision, conceptualization: Zhao, J.

Project administration, funding acquisition, formal analysis: Yuan, X.

Availability of data and materials

The data supporting the findings of this study are available within this Article and its [Supplementary Materials](#). Further data are available from the corresponding authors upon request.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool Doubao (version V13.5.0, released 2026-04-23) was used to generate the small house graphic in the Graphical Abstract based on the authors' descriptions. The AI tool Grammarly Business (Grammarly Inc., Microsoft Word add-in, accessed 2026-07) was used solely for language editing. These AI tools had no involvement in the research design, data collection, data analysis, result interpretation or any scientific content of this work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Zhao, J. is affiliated with Hebei Ledphor Optoelectronics Technology Co., Ltd, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

[Supplementary Materials](#)

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