One Hundred-Nanometer-Sized CsPbBr₃/m-SiO₂ Composites Prepared via Molten-Salts Synthesis are Optimal Green Phosphors for LCD Display Devices

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followed by drying of the solvent), a colloidal synthesis in the presence of silica, or a solid-state reaction (mixing of perovskite precursors and silica, followed by heating up to 700 °C).\[18-25\] The composites obtained with such strategies either lack sufficient stability (colloidal synthesis and impregnation) or behave as bulk-like aggregates (the solid-state reaction leads to the necking/fusion of the silica particles) limiting the use of these materials in practical devices. These drawbacks have been mostly solved in a previous work from our group, in which we have employed a molten-salts-based synthesis approach to prepare stable CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} composites at relatively low temperature (≈350 °C).\[25\] The synthesis protocol is based on a mixture of inorganic salts (KNO\textsubscript{3}, NaNO\textsubscript{3}, and KBr, named molten-salts), which not only act as the reaction medium but also enable the nucleation and growth of CsPbBr\textsubscript{3} NCs in the pores of m-SiO\textsubscript{2} and additionally lead to sealing of the m-SiO\textsubscript{2} pores (via partial etching of silica), de facto burying the perovskite NCs in m-SiO\textsubscript{2}. The final composites featured a high PLQY (≈89%) and good stability against temperature, water and even against an acid environment, surviving for months when immersed in aqueous media (a mixture of HCl and HNO\textsubscript{3}). Still, these composites cannot compete with commercial phosphors for applications in displays,\[16\] mainly for two reasons: (i) the size of the CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} particles is too large (≥600 nm) and when they are embedded in polymer films, they lead to a nonuniform particles distribution and to an excessive light scattering and mass-loading of the phosphors, therefore limiting the efficiency of the device; (ii) the composites feature a low stability under a high flux irradiation in 1000 h accelerated test conditions, leading to a reduced stability of the final device.

In order to solve these problems, in this work, we explored the possibility to optimize the composite size by employing smaller-sized (from 100 to ≈310 nm) m-SiO\textsubscript{2} particles (either prepared by us or using those commercially available) and, additionally, to improve their stability by systematically varying the reaction temperature (which influences the extent of etching of the silica and modulates the pore size) and the molten-salts/perovskite precursors/SiO\textsubscript{2} ratio (which influences the extent of filling of the pores by salts and by CsPbBr\textsubscript{3}). Our results indicated that the best composite, in terms of PLQY and stability against heat, water, and light irradiation, can be obtained by employing m-SiO\textsubscript{2} particles with 100 nm average diameter and by performing the molten-salts synthesis with KNO\textsubscript{3}, NaNO\textsubscript{3}, and KBr molar ratios of 10:5:5 at 320 °C. Such optimized 100 nm-sized CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} nanocomposite features a PLQY as high as 77% and, when embedded in a polymer film, outperforms our previously reported composites\[25\] and also films of standard perovskite NCs\[1\] in terms of stability, by retaining: (i) 94% PL emission after being irradiated with a blue source (450 nm) at a high flux (100 mW cm\textsuperscript{-2}) for 1000 h; (ii) 58% PL emission after being exposed to high temperature (85 °C) for 1000 h; (iii) 100% PL emission after being exposed to high humidity conditions (90% relative humidity, RH) for 1000 h. As best performers, these 100 nm-sized CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} particles were then employed in an actual display device as green phosphors embedded inside a polymer film, delivering an optimal white light (with CIE color coordinates of (0.3067, 0.3271), corresponding to a correlated color temperature (CCT) of 6861 K), which is close to the reference white point of NTSC and covering 92% of NTSC standard color gamut area of CIE1931. The performance of the LCD based on CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} particles was compared with that of a commercial phosphor display (a Dell XPS 15 7590 laptop display, resulting in a higher color gamut. The low preparation temperature, the enhanced stability, and high PLQY with a narrow green emission of the composites reported in the present work outcompete both traditional and newly discovered green phosphors (e.g., Ce\textsuperscript{3+}, Tb\textsuperscript{3+}-codoped NaBaY(BO\textsubscript{3})\textsubscript{2}),\[37,38\] Indeed, such phosphors feature several issues (which do not affect our composites), which are: (i) they need to be synthesized at very high temperatures (800–1100 °C); (ii) the size of the phosphors is very large (in the microns range); (iii) they are characterized either by a very wide PL emission with FWHM around 40–100 nm or by narrow PL emission, as in the case of Ce\textsuperscript{3+}, Tb\textsuperscript{3+}-codoped NaBaY(BO\textsubscript{3})\textsubscript{2}, but the latter is not centered at the green coordinates required by NTSC or Rec.2020 standards. Our composites are therefore ideal candidates for displays and represent a step forward for the implementation of perovskite NCs in actual devices.

2. Preparation and Optimization of CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} Nanocomposites

Our first aim in this work was to produce CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} composites smaller than those we previously reported,\[25\] in order to minimize the light scattering, for use in display applications. We started with the synthesis of m-SiO\textsubscript{2} particles having different sizes and pore diameters. In detail, we employed the synthesis scheme reported by Llopis-Lorente et al.\[19\] to prepare m-SiO\textsubscript{2} particles of either ≈91 ± 14 nm (C1) or ≈196 ± 18 nm (C2) average diameter, measured via the transmission electron microscopy (TEM) analysis (see Figure 1a,b and Figure S1, Supporting Information) and pore size of ≈3.0–3.5 nm, as revealed by the Brunauer–Emmett–Teller (BET) analysis (Figure S2 and Table S1, Supporting Information). The size of these m-SiO\textsubscript{2} particles was regulated by tuning the amount of the structure-directing agent, namely cetyltrimethylammonium bromide, and by varying the injection speed of the silica precursor, that is tetraethyl orthosilicate. We also employed, as an alternative synthesis approach, the one reported by Chiang et al.,\[40\] which yielded ≈169 ± 26 nm m-SiO\textsubscript{2} particles (C3) with pore size of 3.0 nm (Figure 1c; Figures S1–S2 and Table S1, Supporting Information). The difference in C2 and C3 m-SiO\textsubscript{2} particles resides in their different pore volume (namely the volume of the pores per gram of silica) and thus in the volume accessible to perovskite and inorganic salts inside the silica particles: 0.10 cm\textsuperscript{3} g\textsuperscript{-1} for C2 and 0.04 cm\textsuperscript{3} g\textsuperscript{-1} for C3 (Table S1, Supporting Information). In parallel, we also prepared ≈300 nm m-SiO\textsubscript{2} particles (C4) via size selection of commercial mesoporous silica MCM-41, which is actually the same silica employed in our previous work on CsPbBr\textsubscript{3}/m-SiO\textsubscript{2} composites (Figure 1d).\[25\] The size selection was performed by dispersing MCM-41 silica in water (2 mg mL\textsuperscript{-1}) and by centrifuging it at 1157 g for 5 min. The precipitate was discarded and the supernatant was analyzed by dynamic light scattering that yielded a mean size of ≈311 ± 114 nm (Figure S3, Supporting Information) with pore size of

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Figure 1. Structural and optical characterization of m-SiO₂ and CsPbBr₃/m-SiO₂ samples. TEM images of the starting m-SiO₂ nanoparticles: a) C1, b) C2, c) C3, d) C4 m-SiO₂, and of the corresponding CsPbBr₃/m-SiO₂ nanocomposites: e) CsPbBr₃/m-SiO₂_C1, f) CsPbBr₃/m-SiO₂_C2, g) CsPbBr₃/m-SiO₂_C3, h) CsPbBr₃/m-SiO₂_C4. i) HAAD-STEM image of a CsPbBr₃/m-SiO₂_C1 particle with the corresponding EDX maps. j) XRD patterns of CsPbBr₃/m-SiO₂ nanocomposites with the bulk reflections of CsPbBr₃ (ICSD 98-009-7851), KNO₃ (ICSD 98-003-6113), NaNO₃ (ICSD 98-018-0918), and KBr (ICSD 98-005-3826). k) Photoluminescence emission spectra. l) Photographs of CsPbBr₃/m-SiO₂_C1 immersed in aqua regia for 1 year, taken under visible light (upper) and under UV excitation at 365 nm (bottom). m) PLQY of the CsPbBr₃/m-SiO₂ nanocomposites.
3.4 nm (Figure S2 and Table S1, Supporting Information). In this case, the very irregular shape of the particles (Figure 1d) made it challenging to determine their mean diameter via the TEM analysis (which therefore is not reported in the work).

The m-SiO₂ samples were then employed for the preparation of CsPbBr₃/m-SiO₂ nanocomposites via the molten-salts approach that we had previously reported.[25] The synthesis is based on the use of a mixture of KNO₃, NaNO₃, and KBr as the molten salts, which is blended with m-SiO₂ particles and perovskite precursors (CsBr and PbBr₂) at room temperature. The resulting mixture is then heated up to 350 °C for 1 h. Surprisingly, the synthesis parameters optimized for m-SiO₂ particles with size ≥600 nm (our previous work)²⁵ (namely KNO₃:NaNO₃:KBr molar ratio of 10:5:5, CsBr:PbBr₂:(KNO₃+NaNO₃+KBr):m-SiO₂ molar ratio of 2:2:20:5, reaction temperature 350 °C) led to the partial degradation/melting of the small m-SiO₂ particles employed in the current work (Figure S4, Supporting Information). We, therefore, optimized the reaction parameters for the smallest m-SiO₂ sample (that is C1), the one that was more prone to melting and degradation, and systematically varied the perovskite precursors: molten salts:m-SiO₂ molar ratios and the reaction temperature (see the Supporting Information for details; Figures S5–S6 and Table S2, Supporting Information).

We found that the best composites in terms of morphology (i.e., shape and size retention with respect to the starting m-SiO₂) and stability (probed by immersing the product in aqua regia) were obtained with the following reaction parameters: KNO₃:NaNO₃:KBr molar ratio of 10:5:5, CsBr:PbBr₂:(KNO₃+NaNO₃+KBr):m-SiO₂ molar ratio of 6:6:20:5, and reaction temperature 320 °C (Table S2, Supporting Information). In details, the optimized nanocomposite (sample CsPbBr₃/m-SiO₂_C1) was made of particles having the same size and shape as the starting C1 m-SiO₂ (Figure 1e and Figure S7, Supporting Information), a PL emission peaked at 7851) as the majority phase, and a minor fraction of KNO₃, NaNO₃, and KBr (Figure 1j). Interestingly, the PLQY values of these samples (Figure 1m and Table S3, Supporting Information) were observed to vary from 55% ± 5% (sample CsPbBr₃/m-SiO₂_C2) to 80% ± 8% (sample CsPbBr₃/m-SiO₂_C4).

We selected the CsPbBr₃/m-SiO₂_C1 and CsPbBr₃/m-SiO₂_C4 samples as the best candidates to be employed in display applications, given their high PLQY, and we proceeded by testing their stability under accelerated reliability test conditions. To perform such stability tests, we first loaded each composite in a polymer film (via the polymerization of a mixture of composite particles, 0.5 wt%, with a UV curable resin, namely K-129B from Emaxwin) onto a barrier transparent film (FTB3-50 from 3M) made of polyethylene terephthalate with few layers of metal oxide and featuring a water vapor transmission rate of ≈10⁻³ g m⁻² per day at 20 °C (see the Experimental Section for details) as commonly done in displays to prepare the green color conversion layer (as discussed in the next section of this work).

Each composite-polymer film was then subjected to three accelerated reliability tests: (i) high luminous flux (HF), which consists of irradiating the sample via a blue light (450 nm) with a power of 100 mW cm⁻² at 60 °C and 60% RH; (ii) high temperature (HT), which comprises the irradiation of the sample with a blue light (450 nm) with a power of 10 mW cm⁻² at 85 °C and 60% RH; (iii) high humidity (HH), in which the composite is irradiated with a blue light (450 nm) with power of 10 mW cm⁻² at 60 °C and 90% RH. These accelerated test conditions were performed for 1000 h, which correspond roughly to a period of about 3 years under normal operation conditions (i.e., a display operated in the household). The stability of standard perovskite NCs, synthesized using the method reported by Proteescu et al,[1] and the composites reported in our previous work (sample CsPbBr₃/m-SiO₂ ≥ 600 nm)[25] were also tested for comparison. The results are reported in Figure 2.

The outcome of our tests indicated that the polymer films based on 100 nm-sized composites (sample CsPbBr₃/m-SiO₂_C1) featured the best HF, HT, and HH stability, retaining after 1000 h of test 94% of their PL under HF, 58% of their emission under HT, and 100% of their PL under HH. Interestingly, as further proof of their stability, the CsPbBr₃/m-SiO₂-C1-polymer film did not exhibit any edge ingress (degradation that appear from the edges of the film where the particles are not protected by the polymer) upon accelerated test conditions that is typically observed at the edge of quantum dots–polymer films (Figure S9, Supporting Information).

In order to rationalize the high stability of the CsPbBr₃/m-SiO₂_C1 sample, we took into account the following points: (i) standard CsPbBr₃ NCs are not intrinsically stable against HF (Figure 2a, blue curve); (ii) the SiO₂ matrix itself is not able to confer CsPbBr₃ stability against HF, otherwise all the composites would have been HF resistant; (iii) the thickness of...
the m-SiO₂ does not appear to play a major role in conferring HF to perovskite NCs, otherwise the composites made from the biggest m-SiO₂ particles (e.g., CsPbBr₃/m-SiO₂ ≥ 600 nm) would result in the highest HF stability. We therefore hypothesize that the inorganic salts in close contact with CsPbBr₃ NCs inside m-SiO₂ pores can be responsible for the observed HF stability of sample CsPbBr₃/m-SiO₂ C1. Indeed, it has been shown that passivating colloidal perovskite NCs with inorganic salts, such as KBr, can improve their stability[41,42]. In our composites, a different ratio between perovskite NCs and inorganic salts corresponds to a different coverage of CsPbBr₃ NCs with inorganic salts. We evaluated such coverage by measuring the composition (i.e., the Pb/(Na+K) ratio) of our composites via EDX analysis performed in a scanning electron microscope (Table S3, Supporting Information). The sample CsPbBr₃/m-SiO₂ C1 was characterized by the highest Pb/(Na+K) ratio (1.90), followed by CsPbBr₃/m-SiO₂ C4 (with a ratio of 1.01) and CsPbBr₃/m-SiO₂ ≥ 600 nm, the latter featuring the lowest ratio (0.38). This is in agreement with the XRD analysis of these samples: while the XRD pattern of the CsPbBr₃/m-SiO₂ C1 sample was dominated by the reflections from the CsPbBr₃ phase (Figure 1j), that of the CsPbBr₃/m-SiO₂ ≥ 600 nm sample was dominated by the reflections of KNO₃, NaNO₃, and KBr salts (Figure S10, Supporting Information). By comparing the HF stability trend in Figure 2a (CsPbBr₃/m-SiO₂ C1>CsPbBr₃/m-SiO₂ C4>CsPbBr₃/m-SiO₂ ≥ 600 nm) and the Pb/(Na+K) ratio trend, we can hypothesize that an optimal coverage of CsPbBr₃ NCs inside the m-SiO₂ pores by inorganic salts (achieved with a Pb/(Na+K) ratio of 1.90) is responsible for the observed enhanced stability of the CsPbBr₃/m-SiO₂ C1 sample.

3. CsPbBr₃/m-SiO₂-Based Displays

The best composite, CsPbBr₃/m-SiO₂ C1, was then employed to fabricate the green color conversion layer of a proof-of-concept 7-in. LCD display device. To do so, we first prepared a CsPbBr₃/m-SiO₂ C1-polymer film, analogously to that prepared for the stability tests, having a size of 160 mm × 100 mm, and coupled it with a LED magenta backlight source (which consists of a blue LED and a potassium fluorosilicate (KSF) phosphor, which is the same one used for the final down converting LCD display, see the Experimental Section for details). In a series of preliminary tests, the composite’s loading inside the polymer film was tuned in order to obtain an optimal ratio of Red, Green, and Blue (RGB), identifying 0.625 wt% of CsPbBr₃/m-SiO₂ C1 as the appropriate value for the film (Figure 3e). To better estimate the efficiency of the newly prepared composite, we also prepared a polymer film loaded with the CsPbBr₃/m-SiO₂ ≥ 600 nm composite, using the very same loading of 0.625 wt%, as a reference. The thickness of the active layer in both films was 150 µm.

As it is possible to appreciate from Figure 3a, the active polymer film made with CsPbBr₃/m-SiO₂ C1 was characterized by a homogeneous texture with particles being uniformly dispersed through the film, with only a few spots containing aggregates when analyzed under an optical microscope with a blue light source. On the contrary, the use of bigger-sized composites (CsPbBr₃/m-SiO₂ ≥ 600 nm) led to the formation of films featuring almost exclusively large aggregates, clearly visible in the microscale (Figure 3b). The CsPbBr₃/m-SiO₂ C1 polymer film provides a better green color point (i.e., closer to the edge of the CIE1931 color diagram) compared with that of the film.
based on CsPbBr$_3$/m-SiO$_2$ $\geq$ 600 nm particles (Figure 3c,d). The emission of these two films when coupled to a magenta LED backlight was then analyzed to test the green conversion efficiency of the two composites under the same mass loading. The corresponding spectra, shown in Figure 3e,f, revealed that the film based on CsPbBr$_3$/m-SiO$_2$ C1 was characterized by a more intense green emission compared with that based on CsPbBr$_3$/m-SiO$_2$ $\geq$ 600 nm composites, indicating that the newly prepared small composites yielded a better blue-to-green conversion (i.e., higher efficiency) when using the same mass loading. Overall, these preliminary results highlighted that CsPbBr$_3$/m-SiO$_2$ C1 particles outperform the previously reported CsPbBr$_3$/m-SiO$_2$ $\geq$ 600 nm ones in delivering green-converting polymer layers having not only a better texture (i.e., less aggregates and, thus, lower light scattering) but also yielding a more efficient color conversion at equal loadings.

We, therefore, proceeded to the fabrication of the prototype display, by mounting the CsPbBr$_3$/m-SiO$_2$ C1 polymer film in a customized 7-in. LCD display system with magenta LED backlight (Figure 4a–c). The final LCD display was composed of the following stacks (from the bottom to the top): cover, reflector, light guide plate with magenta LED on the sides, CsPbBr$_3$/m-SiO$_2$ C1 polymer composite film, polarizer, and LCD panels (Figure 4a–c). The color gamut of such device was compared with that of a commercial LCD display. For this comparison, we choose a Dell XPS 15 7590 (year 2020) laptop display, in which the red spectrum is generated by a KSF phosphor as in our display setup, so that any difference in the performance of the final device can be ascribed only to the green-converting layer. The white light emitted by the final device had CIE color coordinates of (0.3067, 0.3271), corresponding to a correlated color temperature (CCT) of 6861 K (Figure 4d and Table 1), which
is close to the target white point of the NTSC standard (0.310, 0.316). Moreover, the use of our CsPbBr$_3$/m-SiO$_2$-C$_1$ composites as a green color phosphors in a down-converting LCD display could cover 92% of NTSC standard color gamut area of CIE 1931 (Figure 4d and Table 1). Compared with the commercial LCD display (its color diagram can be found in Figure S11, Supporting Information), the display based on our composite exhibited a superior color gamut performance (see Table 1), which is mainly ascribed to the narrow and bright green emission of the starting CsPbBr$_3$/m-SiO$_2$-C$_1$ particles. To date, commercial displays have been based on green emissive phosphors featuring a quite broad green emission (FWHM ≥26 nm),$^{43}$ which limits the color gamut (Figure S11, Supporting Information). The narrower emission features of our composites combined with their high stability make them particularly promising as green phosphors for down-converting films in LCD displays.

4. Conclusion

In this work, we successfully prepared CsPbBr$_3$/m-SiO$_2$ composites having sizes ranging from 100 to 300 nm via a molten-salt approach. To do so we first prepared m-SiO$_2$ particles with a desired size and then optimized our previously reported molten-salts approach, which is based on the use of a mixture of KNO$_3$, NaNO$_3$, and KBr as the reaction medium, to nucleate CsPbBr$_3$ NCs inside such m-SiO$_2$ particles. The optimization was carried out by systematically varying the reaction temperature and the molten-salts/perovskite precursors/m-SiO$_2$ ratio. The best composite, obtained when employing 100 nm m-SiO$_2$ particles, features a narrow photoluminescence emission (FWHM of 18 nm) and a quantum yield as high as 77%, and, when embedded in a polymer film, it exhibits high stability under high flux (100 mW cm$^{-2}$), high temperature (90 °C), and high humidity (90% RH) up to 1000 h. Interestingly, our

| Sample | CIE color coordinates | Color temperature | Gamut Coverage vs Adobe RGB | Gamut Coverage vs DCI-P3 | Gamut Coverage vs NTSC | Gamut Coverage vs Rec.2020 area |
|--------|-----------------------|-------------------|-----------------------------|--------------------------|-------------------------|--------------------------------|
| CsPbBr$_3$/m-SiO$_2$-C$_1$ | (0.3067, 0.3271) | 6861.1 K | 92.4% | 84.7% | 92% | 78% |
| Dell XPS laptop display | (0.3088, 0.3354) | 6666.7 K | 74% | 74% | 71% | 53% |

Table 1. Color gamut performance of LCD display utilizing CsPbBr$_3$/m-SiO$_2$-C$_1$ as compared with commercial display using green phosphor.
results indicate that the resistance to a high flux is not conferred by the silica itself, but by the inorganic salts in close contact to CsPbBr$_3$ NCs inside SiO$_2$ pores only at an optimal perovskite/salts ratio (namely Pb/(Na+K) of 1.9). These characteristics make such composite particles ideal candidates (even more promising than CsPbBr$_3$@SiO$_2$ core@shell NCs) as green phosphors in LCD displays. We, therefore, tested them in the green color conversion film of a proof-of-concept 7-in. LCD. The resulting device is characterized by an optimal white light which is close to the reference white point of NTSC (with CIE color coordinates of (0.3067, 0.3271)), corresponding to a correlated color temperature (CCT) of 6861 K and covers 92% of NTSC standard color gamut area of CIE1931, that is a higher color gamut than that of a commercial phosphor display (a Dell XPS 15 7590 laptop display). This work demonstrates an efficient approach to obtain highly stable lead halide perovskite composites that can be deployed in real devices. A further shift of the PL of such composites in the green (ideally reaching a PL peak at 530 nm), for example, via the formation of CsPb(Br$_3$I)$_4$ NCs inside the m-SiO$_2$ particles, should be the next challenge to overcome in order to produce displays with an even broader gamut area. Considering the toxicity of lead and its possible restrictions in international product markets, we believe that a straightforward exploitation of the present synthetic strategy should be the production of composites featuring nontoxic metal halide nanocrystal systems, allowing for their exploitation in optoelectronic devices.

## 5. Experimental Section

### Chemicals

Tetraethyl orthosilicate (TEOS, 99%), sodium hydroxide (NaOH, 98%), silica (mesostructured, MCM-41 type, product code 643 645), cesium bromide (CsBr, 99.9%), lead acetate (Pb(Br$_2$, 98%), potassium nitrate (KNO$_3$, 99.999%), sodium nitrate (NaNO$_3$, 99.995%), potassium bromide (KBr, 99%), triethoxycyanacetate silane (90%), 1-octadecene (ODE, 90%), dimethyl sulfoxide (DMSO, 99.9%), ethanol (99.9%), toluene (anhydrous, 99.9%), and acetone (99.9%) were purchased from Sigma-Aldrich. Cetyltrimethylammonium bromide (CTABr, 98%) was purchased from MP Biomedicals, LLC. UV curable polymer resin (K-1292B) was purchased from Emauxin. Flexible transparent barrier film (3M FTB Film 3–50) was purchased from 3 M. All chemicals were used without any further purification.

### Preparation of m-SiO$_2$ (C1, C2, and C3) Nanoparticles

Mesoporous m-SiO$_2$ (C1) particles were synthesized by employing a modified Stober method with minor changes.[39] First, 2.74 mmol of CTABr was dissolved in 480 mL of deionized (DI) water and the pH of the solution was basified via the addition of 3.5 mL of a NaOH solution (2 M in DI water). The mixture was heated up to 70 °C and then 22.4 mmol of TEOS was injected with a speed of 10 mL min$^{-1}$ while the solution was vigorously stirred. The reaction mixture was stirred for 3 h at 70 °C and the product was collected via centrifugation at 10 000 rpm for 10 min. The precipitate was washed with DI water for five times and then dried at 40 °C for 24 h. The precipitate was redissolved by sonicating the mixture for 10 min, centrifuging it at 10 000 rpm for 10 min, and collecting only the precipitate. The final products were eventually dried at 40 °C in a vacuum oven.

### Powder X-Ray Diffraction (XRD)

XRD patterns were collected on a PANalytical Empyrean X-ray diffractometer, equipped with a 1.8 kW Cu Kα ceramic X-ray tube, and a PIIXcEld 3 × 2 area detector, operating at 45 kV and 40 mA. Samples of XRD were prepared by pressing the composite powders onto a quartz zero-diffraction single-crystal substrate. The diffraction patterns were collected under ambient conditions using a parallel beam geometry and the symmetric reflection mode. XRD data analysis was conducted on the HighScore 4.1 software from PANanalytical.

### Transmission Electron Microscopy (TEM)

#### Characterization: Diluted composite dispersions were drop-cast onto copper TEM grids with an ultrathin carbon film. Low-magnification TEM images were acquired on a JEOL JEM-1400Plus microscope with a thermionic gun (W filament), operated at an acceleration voltage of 120 kV. Scanning transmission electron microscopy (STEM) images were acquired on a probe-corrected ThermoFisher Spectra 300 S/TEM operated at 300 kV. Images were acquired on a High-Angle annular Dark Field (HAADF) detector with a current of ~2 pA. Compositional maps were acquired and processed using Velox and rapid rastered scanning. The energy-dispersive X-ray (EDX) signal was acquired on a Dual-X system comprising two detectors either side of the sample, for a total acquisition angle of 1.76 Sr.

#### Dynamic Light Scattering (DLS)

DLS measurements were conducted on a Zetasizer Nano S from Malvern Pananalytical. m-SiO$_2$ powders were sonicated and dispersed in DI water for the measurements.

### Specific Surface Area and Porosity Measurements

Specific surface area and porosity measurements were carried out by nitrogen physisorption at 77 K with an automated gas sorption analyzer (AutoSorb iQ, Quantachrome Instruments). Prior to measurements, the samples were outgassed overnight at 300 °C under vacuum conditions to remove any adsorbed species. Specific surface areas were calculated by the multipoint Brunauer–Emmett–Teller (BET) method,[46] considering equally spaced points in the P/P$_0$ range from 0.05 to 0.30 with a correlation coefficient of above 0.999. Pore-size distribution and pore volume were determined by the Barrett–Joyner–Halenda (BJH) method using the adsorption branch of the capillary condensation region.[47]

### Scanning Electron Microscopy (SEM) with Energy-Dispersive X-Ray Spectroscopy (EDX)

SEM analysis was conducted on a HRSEM Jeol JSM-7500LA microscope with a cold field-emission gun (FEG), working at 15 kV acceleration voltage. Energy-dispersive spectroscopy (EDX; Oxford instrument, X-Max, 80 mm$^2$) was used to evaluate the elemental ratios. All experiments were carried out at 8 mm working distance, 15 kV acceleration voltage, and 15 sweep count for specimens.

### Optical Properties

The PL spectra were measured on a Varian Cary Eclipse spectrophotometer with an excitation wavelength of 350 nm. The composites were dispersed in water. The PLQY measurements were performed using the spectrophotometer F55 from Edinburgh.
instrument equipped with integrating sphere. The color coordinates, color diagram, and RGB spectra of the display were measured using a spectral luminance meter SRI-RL-5000 from Optimum.

Preparation of Polymer–Composite Films: A desired amount of CsPbBr3/m-SiO2 nanocomposites was dispersed in 2 mL of acetone and sonicated for 2 min, after which an UV curable polymer resin (K-129B from Emawin) was added and the resulting mixture was stirred overnight inside an open vial (under a fume hood) to evaporate all the acetone. The role of acetone in this initial step is that of ensuring the complete dispersion of the composite particles in the highly viscous resin. The mixture was deposited onto a barrier transparent film (FTB3-50 from 3M with a thickness of 50 µm) made of polyethylene terephthalate with few layers of metal oxide (featuring a water vapor transmission rate of ~10−1 g m−2 per day at 20 °C) via blade coating, producing a final film having a total thickness of ~250 µm, which was irradiated with an UV source for 1 min to cure the polymer resin. The cured film was eventually cut according to the size needed for the display. The concentration of the composites in the polymer film was 0.5 wt% in the stability tests, while for the display we used a concentration of 0.625 wt%. The polymer films based on standard perovskite NCs were made using the same approach with the only difference being the preparation of the polymerizable mixture, which was realized by simply mixing the colloidal NCs with the resin.

Reliability Tests: The reliability tests of the polymer films containing either CsPbBr3/m-SiO2 composites or standard perovskite NCs were performed under custom made setups. In details, the high flux (HF) tests were done in a customized system consisting of a blue (450 nm) emitting light source (model XYUV-4II from Eight-LED company) with adjustable power and a standard hot plate to control the temperature of the sample. During the HF tests, the source power was set at 100 mW cm−2, the temperature was 60 °C and the RH was 60%. The high temperature (HT) tests were done in the same customized setup in which the irradiation power was set at 10 mW cm−2, the RH was 60%, and the temperature of the hot plate was 85 °C. On the other hand, the high humidity (HH) tests were performed in humidity and temperature chamber (model LHU-113 from Espec Corp.). During the HH test, the temperature was set at 60 °C, the RH at 90%, and the irradiation power was set at 10 mW cm−2. The stability of the polymer films, having a size of 5 cm × 5 cm, was tested by inserting them in these systems for around 1000 h (42 days) and by periodically measuring their PL intensity.

Fabrication of the Liquid Crystal Display (LCD): The 7-in. LCD display was purchased from Lincoln Technology Solution and customized. The polymer film made with CsPbBr3/m-SiO2 Cl composite particles was cut into a 160 × 100 mm2 and placed in the LCD display stacks. The stacks of the final device, going from the bottom to the top, consist of: cover, reflector, light guide plate with magenta LED on the side (backlight), CsPbBr3/m-SiO2 Cl polymer composite film polarizer, and LCD panel. The LCD panel and the backlight are controlled by an integrated circuit corresponding author upon reasonable request.

Data Availability Statement

The data that support the findings of this study are available from the Wiley Online Library or from the author.

Keywords

CsPbBr3/m-SiO2 composites, displays, high flux stability, high temperature stability, molten-salt reaction

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

L.M. is in the Advisory Board of Quantum Solutions.
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