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Efficient and Stable CsPb(Br/I)₃@Anthracene Composites for White Light-Emitting Devices

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Abstract

Inorganic perovskite quantum dots bear many unique properties that make them potential candidates for optoelectronic applications, including color display and lighting. However, the white emission with inorganic perovskite quantum dots has rarely been realized due to the anion-exchange reaction. Here, we proposed a one-pot preparation to fabricate inorganic perovskite quantum dot-based white light-emitting composites by introducing anthracene as a blue emission component. The as-prepared white light-emitting composite exhibited a photoluminescence quantum yield of 41.9%. By combining CsPb(Br/I)₃@anthracene composites with UV light-emitting device (LED) chips, white light-emitting devices with a color rendering index of 90 were realized with tunable color temperature from warm white to cool white. These results can promote the application of inorganic perovskite quantum dots in the field of white LEDs.

Graphical Abstract

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Supporting Information

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Materials; synthesis; purification; fabrication of WLEDs; material characterizations, such as energy-dispersive X-ray (EDX) spectra, X-ray photoelectron spectra, fluorescence lifetime measurements, time stability, and temperature stability-related PL spectra; and emission spectra related to anion exchange (PDF)

Notes

The authors declare no competing financial interest.

Keywords

perovskite; quantum dot; anthracene; white light; LED

INTRODUCTION

Recently, inorganic perovskite quantum dots (QDs) CsPbX_3 ($X = \text{Cl}, \text{Br}, \text{I}$, or mixture of them) have attracted extensive attentions in the fields of light-emitting diodes,^{1–4} lasing,^{5,6} display,^{7–9} and solar cells,^{10–12} with their unique optical properties encompassing high extinction coefficient, narrow emission spectrum, and high photoluminescence quantum yield (PLQY).^{5,13–17} Moreover, the emission wavelength of perovskite QDs can be easily tuned over the entire visible spectral region by varying halide anions,^{18,19} which endows inorganic perovskite QDs with a promising future to be designed as nanophosphors.^{16,20} However, the anion-exchange reaction between different halide inorganic perovskites on the other hand limits their application in white light-emitting devices (WLEDs).^{18,19,21,22}

To solve this problem, Rogach and co-workers obtained CsPbBr_3 and $\text{CsPb}(\text{Br/I})_3$ QDs coated by polyhedral oligomeric silsesquioxane.²³ Some groups avoided anion-exchange reaction by constructing a silica shell or synthesizing $\text{CsPbX}_3/\text{zeolite-Y}$ composite phosphors.^{8,16,24,25} In these studies, although the anion-exchange reaction was restrained, the multistep synthesis and long-time treatment were normally needed. Additionally, the white light emissions were achieved by mixing a multilayer of green and red perovskite phosphors with blue InGaN chips, which suffered from the low color rendering index (CRI) and high correlated color temperature (CCT) that varied with working voltage and phosphor coating thickness.^{26,27} Very recently, single-phase white materials have been reported; these materials emit white light through doping perovskites.^{28–30} Nevertheless, these processes are generally complex.³¹

In this communication, we describe a type of white light-emitting $\text{CsPb}(\text{Br/I})_3/\text{anthracene}$ composites by a one-pot synthesis. The advantage of this approach lies on the fact that $\text{CsPb}(\text{Br/I})_3/\text{anthracene}$ composites were prepared directly without post-treatment, and the anthracene component not only worked as a blue-emitting component, but also acted as an absorption antenna to sensitize the PL of perovskite QDs. The as-prepared perovskite@anthracene composites exhibited broad emission bands spanning from 400 to 650 nm that resulted in a white light emission with a PLQY of 41.9%. The stability was also increased because of the surrounding anthracene for QDs.

Furthermore, WLEDs with Commission Internationale de l'Eclairage (CIE) 1931 color coordinates of (0.35, 0.30) were fabricated by combining CsPb(Br/I)₃@anthracene composites with UV chips. A CRI of 90 and tunable CCT from 2911 to 8572 K were successfully achieved by involving the different mass ratios of green and red CsPb(Br/I)₃@anthracene composites powder.

RESULTS AND DISCUSSION

In our experiment, anthracene (C₁₄H₁₀, chemical structure shown in Figure S1) was introduced during the synthesis of CsPb(Br/I)₃ QDs. PbBr₂, PbI₂, and anthracene are foremost dissolved in a mixture of octadecene (ODE), oleylamine (OLA), and oleic acid (OA) under vacuum at 120 °C to produce a precursor solution. Subsequently, a cesium-oleate solution in ODE was swiftly injected and CsPb(Br/I)₃ QDs immediately formed. The CsPb(Br/I)₃@anthracene composites were precipitated out when the temperature was cooled to room temperature in an ice-water bath.

Powder X-ray diffraction (XRD) analysis for pure CsPb(Br/I)₃ QDs, pure anthracene, and CsPb(Br/I)₃@anthracene composites with distinct perovskite QD concentrations (C1, C2, and C3, respectively) are compared in Figure 1a. The as-prepared composites C1, C2, and C3 present similar diffraction peaks at 19.1, 21.1, 25.2, 29.0, and 38.9° that can be attributed to (200), (002), (-202), (300), and (400) planes of the monoclinic phase of anthracene crystals (JCPDS no. 04-0300).³² Two additional diffraction peaks appeared at 14.7 and 29.8° that can be assigned to (100) and (200), respectively, of cubic perovskite structure (JCPDS No. 54-0752) by comparing to those of the pure CsPb(Br/I)₃ QDs. To see these two diffraction peaks more clearly, we show the enlarged sections at ranges of 13.0–17.0 and 28.0–32.0° in the right panel of Figure 1a.³³ Moreover, the molar mass concentrations of the CsPb(Br/I)₃ QDs inside composites were identified to be 13.09, 17.76, and 23.21 μmol/g for C1, C2, and C3, respectively, by inductively coupled plasma mass spectrometry.

Fourier transform infrared (FTIR) spectral studies were performed using the KBr pelleting technique. The FTIR spectra of pure CsPb(Br/I)₃ QDs, pure anthracene, and the CsPb(Br/I)₃@anthracene composites C1, C2, and C3 presented similar FTIR vibration features: a characteristic peak due to aromatic C–H stretch located at around 3047 cm⁻¹. The sharpness of the peak illustrates that the hydrogen atoms in the anthracene ring are not exerting any bonding interaction with molecules.^{34,35} Peaks at 1620, 1532, and 1447 cm⁻¹ can be assigned to the skeletal vibrations (C=C bond) of benzene ring, and the peaks at 725 and 883 cm⁻¹ are referred to the plane bended and the disubstituted benzene ring. These vibrations are completely consistent with those in pure anthracene crystals, as shown in Figure 1b.^{34,36,37} Besides these peaks, it is also found that two additional vibrations 2854 and 2923 cm⁻¹ appeared in the composites compared with anthracene crystals, which can be related to the symmetrical and asymmetric stretching vibrations of CH₂ and CH₃ of OLA and OA molecules anchored on the surface of perovskite QDs (Figure 1b, right panel). These results indicated that the composites are consisted of perovskite QDs and anthracene crystals.³

From the energy-dispersive X-ray (EDX) spectra, the atomic ratio of Cs/Pb/Br/I of the as-prepared CsPb(Br/I)₃@anthracene composite C2 can be identified as 1.0:1.0:1.7:1.1 (Figure S2), indicating that CsPb(Br_{0.6}I_{0.4})₃ QDs formed in the composite. X-ray photoelectron spectra (XPS) further confirmed the EDX results. From Figure S3, main peaks of Cs 3d, Pb 4f, Br 3d, and I 3d have the similar binding energies compared to those of inorganic perovskite QDs prepared by other methods.^{13,16} The Cs/Pb/Br/I atomic ratio can be identified to be 1.1:1.0:1.6:1.1 from the XPS peak areas of survey spectra in Figure S3a, which is consistent with the EDX results. The morphology of the as-prepared CsPb(Br_{0.6}I_{0.4})₃@anthracene composite was investigated through transmission electron microscopy (TEM, Figure 2). As shown in Figure 2a–c, the spherelike inorganic perovskite QDs were embedded in anthracene host crystals evenly for the as-prepared C1, C2, and C3 samples. The size distribution histograms of perovskite QDs are calculated from their TEM images, which exhibited average diameters of 2.5 ± 0.5 , 2.4 ± 0.4 , and 2.4 ± 0.4 nm for CsPb(Br_{0.6}I_{0.4})₃ QDs in C1, C2, and C3, respectively (inset of Figure 2a–c). Apparently, the QDs had the same size for the three samples.

High-resolution transmission electron microscopy (HRTEM) images for the typical CsPb(Br_{0.6}I_{0.4})₃@anthracene composite C2 sample are presented in Figure 2d, in which a good crystallinity was observed, and the lattice fringes of 0.29 and 0.41 nm were identified from the (210) diffraction plane of the CsPb(Br_{0.6}I_{0.4})₃ QDs and (111) plane of anthracene, respectively. The high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image showed clearly the distribution of the CsPb(Br_{0.6}I_{0.4})₃ QDs in the composite (Figure 2e), and the elemental mapping result exhibited that the Cs, Pb, Br, and I atoms were uniformly distributed in the CsPb(Br_{0.6}I_{0.4})₃@anthracene composite (Figure 2f).

The optical properties of the material are shown in Figure 3. The blue emission was observed from anthracene crystals under an ultraviolet irradiation of 365 nm, whereas the as-prepared C1, C2, and C3 composites exhibited intense white light PL (Figure 3a). The normalized absorption spectra of pure CsPb(Br_{0.6}I_{0.4})₃ QDs solution, pure anthracene, and CsPb(Br_{0.6}I_{0.4})₃@anthracene composite C2 (dissolved in n-hexane) are shown in Figure 3b. From the absorption spectra, the anthracene exhibited five absorption peaks at around 307, 322, 338, 355, and 374 nm that can be related to the $\pi-\pi^*$ transition of organic anthracene.³⁸ And the pure CsPb(Br_{0.6}I_{0.4})₃ QDs presented a strong and broad absorption from 300 to 580 nm (Figure 3b); its first excitonic peak was measured at 558 nm (inset of Figure 3b). Besides, the first absorption peak (306 nm) of anthracene in composites blue-shifts around 1 nm compared to that (307 nm) of pure anthracene, which can be attributed to conformational changes of the anthracene because of the interaction between anthracene molecular and perovskite QDs.³⁹ Actually, anthracene has a conjugated benzene structure, which is a strong electron-withdrawing group,⁴⁰ and perovskite QDs are passivated by halogen anions. It is well known that iodine anion is a soft base, which is easily deformed and gives electrons.⁴¹ When the perovskite QDs are embedded into anthracene, the electrons of iodine will transfer to anthracene, which causes a change in the optical performance of the anthracene. This hypothesis can be proved by the XPS data of the iodine (Figure S4), in which the binding energy of iodine moves to the higher energy side.

The emission spectra of pure CsPb(Br_{0.6}I_{0.4})₃ QDs, pure anthracene, and CsPb(Br_{0.6}I_{0.4})₃@anthracene composites are presented in Figure 3c. The composites C1, C2, and C3 exhibit broad emission bands spanning over almost the entire visible spectral region, in which the distinct emitting components overlapped. It is clear to observe that emission peaks of the composites centered at 426, 443, 469, 503, and 546 nm are almost identical with the $\pi-\pi^*$ transitions (purple line in Figure 3c) in the pure anthracene^{42,43} and the band at 590 nm is similar to the excitonic emission band (orange line in Figure 3c) of CsPb(Br_{0.6}I_{0.4})₃ QDs,²⁵ which indicates that emissions from CsPb(Br_{0.6}I_{0.4})₃@anthracene composites are actually resulted from the contribution of both anthracene and perovskite QDs.⁴⁴ Moreover, it is intriguing to find that the relative intensity of the peaks at 426 nm to the one at 443 nm in composites compared to that of the pure anthracene clearly increased and shifted to blue in wavelength, which is consistent with the absorption result due to the conformational changes of anthracene.³⁹ In addition, the emission peak around 590 nm of CsPb(Br_{0.6}I_{0.4})₃ QDs in the composites shifted to longer wavelength comparing with 580 nm of the pure QDs, and the shift increased with more CsPb(Br_{0.6}I_{0.4})₃ QDs in the composites, which mainly resulted from the QD's self-absorption in solid-state host matrix.^{16,45} With the inorganic QD concentrations in the composites increasing, it is also found that the relative intensity of excitonic transition of QDs to $\pi-\pi^*$ transition of anthracene increased obviously. The emission features are further quantified through the measurement of the absolute emission QY for the pure perovskite QDs and CsPb(Br_{0.6}I_{0.4})₃@anthracene composites, and the QY values for the pure perovskite QDs, composites C1, C2, and C3 are 66.7, 36.8, 41.9, and 34.5%, respectively.

Additionally, the energy transfer is expected to occur from anthracene to CsPb(Br_{0.6}I_{0.4})₃ QDs in the perovskite@anthracene composites because the blue emission of anthracene overlapped well with the absorption of CsPb(Br_{0.6}I_{0.4})₃ QDs.^{39,46} The energy transfer mechanism from the anthracene to CsPb(Br_{0.6}I_{0.4})₃ QDs is revealed through the analysis of the time-resolved photoluminescence decays of the $\pi-\pi^*$ transitions of anthracene in the perovskite@anthracene composites (Figures 4a and S5–S8). The photoluminescence decay of anthracene becomes faster when introducing CsPb(Br_{0.6}I_{0.4})₃ QDs, and the average time constant decreased with the increase of the QD concentration (Figure 4b and Table S1), which confirmed that the energy of the anthracene host transferred to the embedded inorganic perovskite QDs, and the efficient energy transfer happened from emission peaks at 426 and 443 nm of anthracene to the excitonic levels of CsPb(Br_{0.6}I_{0.4})₃ QDs. The energy transfer efficiency η can be calculated by the following formula

$$\eta = 1 - \frac{\int \text{PL}_{\text{DA}}(E) dE}{\int \text{PL}_{\text{D}}(E) dE} = 1 - \frac{\tau_{\text{DA}}}{\tau_{\text{D}}}$$

where τ_{D} and τ_{DA} stand for the amplitude-averaged lifetimes of the donor in the absence and presence of acceptor, respectively.^{32,47} The calculated energy transfer efficiency is shown in Figure 4c and Table S2, indicating that the energy transfer efficiency from the peak at 426 nm is much higher than that of other peaks.

Stability of CsPb(Br_{0.6}I_{0.4})₃@anthracene composite C2 at different aging times was investigated under the UV excitation of 365 nm for 24 h. From Figure S9a, although the excitonic emission associated to CsPb(Br_{0.6}I_{0.4})₃ QDs in the composite exhibited little blue shift due to the phase separation between Br⁻ and I⁻ anions,⁴⁸ the stability of composite is improved obviously compared to that of the pure CsPb(Br_{0.6}I_{0.4})₃ QDs (Figure S9b). Furthermore, we also evaluated the thermal stability of the CsPb(Br_{0.6}I_{0.4})₃@anthracene composite, as shown in Figure S10a. In general, the inorganic perovskite QDs are unstable at higher temperatures particularly for QDs containing I⁻ ions.^{16,49} The quenching temperature (defined as the temperature of the emission intensity decreased to 50% of the original values) of excitonic emission of QDs in the composite was calculated to be 100 °C, which is much higher than that of pure QDs (T_q = 50 °C, Figure S10b).^{8,25} This result indicates that the thermal stability of perovskite QDs is dramatically improved in the composite and also indicates a promising future to be applied as white light-emitting nanophosphors. Moreover, CsPb(Br_{0.6}I_{0.4})₃@anthracene composite exhibits a good air stability for the PL performance compared to that of pure CsPb(Br_{0.6}I_{0.4})₃ QDs (Figure S11). From Figure S11, the bright white light emission is observed in CsPb(Br_{0.6}I_{0.4})₃@anthracene composite under UV light after being stored for 11 months, whereas the pure CsPb(Br_{0.6}I_{0.4})₃ QDs show dim emission under the UV excitation after only a month aging time under the air.

UV-pumped WLEDs were fabricated through the combination of 385 nm UV chips with the as-prepared CsPb(Br_{0.6}I_{0.4})₃@anthracene composite C2. It is necessary to note that a remote-type structure was employed for preparing the device, in which the phosphor layer was separated from the exciting LED p-n junction to reduce the thermal effect.^{16,50,51} The WLEDs with CIE color coordinates of (0.35, 0.30) are obtained by mixing composite C2 and poly(methyl methacrylate) in toluene, evaporating toluene, and then irradiating by a 385 nm UV light. The emission spectra of the WLEDs at different forward voltages are presented in Figure 5a. The electroluminescence (EL) intensities of both anthracene and CsPb(Br_{0.6}I_{0.4})₃ QDs increase with the forward current indicating that CsPb(Br_{0.6}I_{0.4})₃@anthracene composite exhibited no saturation toward UV light. The color coordinates of WLEDs shift slightly with the increased working voltage; x and y change less than 0.03 (Figure 5b). Meanwhile, the LED based on solidified pure CsPb(Br_{0.6}I_{0.4})₃ QDs was also fabricated, and the time-dependent EL intensity curves of the devices with pure QDs and composite C2 are presented in Figure 5c. The EL intensity of LEDs based on pure CsPb(Br_{0.6}I_{0.4})₃ QDs decreased to 10% of its original luminous intensity within an hour; in contrast, the WLEDs based on composite C2 still keep good optical performance. This result can be further supported by the experiment photos exhibited in Figure 5d, which show the variation of the EL intensity for the two devices versus working time. The LED based on pure QDs degraded more rapidly compared with the WLED based on composite C2.

To obtain WLEDs with adjustable CCT, we synthesized green light-emitting CsPb(Br_{0.8}I_{0.2})₃@anthracene and red light-emitting CsPb(Br_{0.4}I_{0.6})₃@anthracene composites, with emission peaks at 531 and 623 nm, respectively (Figures S12 and S13).⁵² Figure S13 shows the emission spectra of CsPb(Br_{0.8}I_{0.2})₃@anthracene and CsPb(Br_{0.4}I_{0.6})₃@anthracene composites excited by 385 nm UV light. By varying the mass ratio of CsPb(Br_{0.8}I_{0.2})₃@anthracene and CsPb(Br_{0.4}I_{0.6})₃@anthracene composites, the EL emission spectra of WLEDs could be adjusted, as shown in Figure 6a and Table 1. The white

light emission becomes cooler with the increase of green light-emitting component and the decrease of red light-emitting component. Table 1 shows the characteristics of the as-fabricated WLEDs, including CCT, CIE 1931 coordinate, and CRI. For the WLEDs based on the distinct mass ratio of green and red light-emitting phosphors, the CIE color coordinates of (0.30–0.40, 0.27–0.36) in the white light region (Figure 6b) and CRI values ranged from 72 to 90 can be achieved. Figure 6c gives the working images of the as-prepared devices, demonstrating their tunable CCT from warm (2911 K) to cool (8572 K) white light (Figure 6b,c).

Normally, the anion exchange is a main issue to influence the device performance and prevents the perovskite QDs to realize the white light emission. Therefore, we further investigated anion exchange between green light-emitting $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ @anthracene and red light-emitting $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ @anthracene composites. It was performed by comparing the time-dependent PL spectra for the mixture of $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ @anthracene and $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ @anthracene composites to those for the mixture of pure $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ and $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ QDs (as shown in Figure S14). Although the anion exchange still happens when redispersing the composites into toluene (Figure S14), it can be efficiently avoided in the solid state of the perovskite@anthracene composites. As shown in Figure S15a, the green light emission (531 nm) and the red light emission (623 nm) can be related to the excitonic transition of perovskite QDs in $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ @anthracene composite and $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ @anthracene composite, respectively. It is found that there are no obvious shifts for emission bands or the variation of spectral shape in 30 h and only slight decrease of PL intensity could be observed for red light emission (Figure S15a). On the contrary, in the emission spectra for the mixture of pure $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ and $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ QDs, the green light emission related to the $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ QDs and red light emission associated to the $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ QDs evolved to one emission band centered at around 560 nm after 45 min (Figure S15b). These results indicate that anion exchange was efficiently avoided in perovskite@anthracene composites. Therefore, it can be concluded that anthracene crystals protected the perovskite QDs from the anion exchange.

CONCLUSIONS

We synthesized white light-emitting $\text{CsPb}(\text{Br}_{0.6}\text{I}_{0.4})_3$ @anthracene composites, which avoided anion-exchange reaction. Subsequently, we fabricated WLEDs with CIE 1931 color coordinates (0.35, 0.30) using white light-emitting $\text{CsPb}(\text{Br}_{0.6}\text{I}_{0.4})_3$ @anthracene composite powder with UV LED chips. The WLEDs show excellent color stability against the increase voltage, and there is no saturation to the UV light within a wide range of working voltages. In the end, we have combined green and red $\text{CsPb}(\text{Br/I})_3$ @anthracene composites powder with UV chips to obtain WLEDs with high CRI and adjustable CCT from warm to cool white light.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(a) X-ray powder diffraction (XRD) pattern of the pure QDs, pure anthracene crystals, C1, C2, and C3; right two panels are the magnified signals from the yellow marked angles. (b) Fourier transform infrared (FTIR) spectra of pure QDs, pure anthracene, C1, C2, and C3 and enlarged section of 2700–3000 cm⁻¹ (right panel).

Figure 2.

(a–c) TEM images of $\text{CsPb}(\text{Br}_{0.6}/\text{I}_{0.4})_3$ @anthracene composites C1, C2, and C3. The insets show size distributions of QDs measured from TEM. (d1) High-resolution transmission electron microscopy (HRTEM) image of $\text{CsPb}(\text{Br}_{0.6}/\text{I}_{0.4})_3$ @anthracene composite C2 and enlarged HRTEM images of (d2) inorganic perovskite QDs and (d3) anthracene crystals. (e) High-angle annular dark-field scanning TEM (HAADF-STEM) image of $\text{CsPb}(\text{Br}_{0.6}/\text{I}_{0.4})_3$ @anthracene composite. (f) Elemental mappings of inorganic perovskite QDs of a selected area in (e).

Figure 3.

(a) Photographs of pure anthracene and CsPb(Br_{0.6}I_{0.4})₃@anthracene composites C1, C2, and C3 under room light and UV light. (b) Absorption spectra of pure anthracene, pure QDs, and CsPb(Br_{0.6}I_{0.4})₃@anthracene composite C2; the inset is the enlarged absorption spectra of composite C2 and pure CsPb(Br_{0.6}I_{0.4})₃ QDs from 450 to 600 nm. (c) Emission spectra of the pure QDs, pure anthracene, and the as-prepared CsPb(Br_{0.6}I_{0.4})₃@anthracene composites with different QD concentrations under the excitation of 385 nm UV light.

Figure 4.

(a) Time-resolved PL decays for pure anthracene crystals and $\text{CsPb}(\text{Br}_{0.6}\text{I}_{0.4})_3$ @anthracene composites C1, C2, and C3 monitored at the 426 nm under the excitation of 365 nm. (b) Average lifetimes of anthracene emission at 426, 443, 469, 503, and 546 nm in anthracene and $\text{CsPb}(\text{Br}_{0.6}\text{I}_{0.4})_3$ @anthracene composites C1, C2, and C3. All of the samples are excited at 365 nm. (c) Energy transfer efficiencies at specific wavelengths.

Figure 5.

(a) EL spectra of the WLED as a function of working voltage. (b) The CIE 1931 color coordinates of the WLED device measured at different working voltages. (c) Time-dependent EL intensities of the LEDs based on pure QDs and composite C2, respectively. (d) Photos of LEDs based on pure QDs (yellow light emission) and composite C2 (white light emission) at different working times, respectively.

Figure 6.

(a) EL spectra of UV LED chips coated with a mixture of green light-emitting $\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ @anthracene and red light-emitting $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ @anthracene composites powder with various mass ratios. (b) CIE 1931 color coordinates of WLED devices A–G. (c) True-color images of WLED devices A–G.

Table 1.

CCT, CIE 1931 Coordinates (x , y), CRI, and Mass Ratios ($\text{CsPb}(\text{Br}_{0.8}\text{I}_{0.2})_3$ @Anthracene: $\text{CsPb}(\text{Br}_{0.4}\text{I}_{0.6})_3$ @Anthracene Composites Powder) of WLEDs A–G

device	CCT (K)	CIE 1931 (x , y)	CRI	mass ratio
A	2911	(0.40, 0.32)	72	1:4
B	3730	(0.37, 0.32)	75	1:2.3
C	4485	(0.36, 0.36)	86	1:1.5
D	5520	(0.33, 0.33)	90	1:0.8
E	6093	(0.32, 0.36)	82	1:1
F	7134	(0.30, 0.32)	83	1:0.67
G	8572	(0.30, 0.27)	80	1:0.43