Polymer additive engineering of $\text{K}_2\text{CuBr}_3$ nanocrystalline films to achieve efficient and stable deep-blue emission

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Abstract

Recently, non-toxic alternatives to lead-halide perovskites have been greatly sought after in optoelectronics applications. Deep-blue luminescent material is mainly required for fabricating white light source and expanding the color gamut of full-color displays. However, the synthesis of high-performance lead-free perovskite films with efficient blue emission is still a critical challenge currently, limiting their further practical applications. Here, a novel strategy is reported to prepare non-toxic and deep-blue-emitting $\text{K}_2\text{CuBr}_3$ nanocrystalline films by introducing polymer poly(methyl methacrylate) (PMMA) additives into the anti-solvent. It is found that the PMMA additives could effectively reduce the grain size and improve the crystallinity of $\text{K}_2\text{CuBr}_3$ films, resulting in an enhanced radiative recombination by defect passivation and confinement of excitons in the nanograins. As a result, the PMMA-treated $\text{K}_2\text{CuBr}_3$ films achieve a bright deep-blue light with color coordinates at (0.155, 0.042), and the photoluminescence quantum yield obtained is about 3.3 times that of the pristine sample. Moreover, the treated $\text{K}_2\text{CuBr}_3$ films exhibit a substantially enhanced stability under harsh environmental conditions, maintaining >70% of their initial performances in high humidity environment (50%–70% humidity, 190 h) or under uninterrupted ultraviolet light radiation (254 nm, 3.4 mW cm$^{-2}$, 150 h). These findings pave a promising strategy for achieving efficient and stable deep-blue metal halide films, showing their potential applications in optoelectronic devices.

1. Introduction

Since 2014, lead-halide perovskites have shown tremendous potential in the photoelectric field and received strong attention due to their arresting photoelectric properties, such as high photoluminescence quantum yield (PLQY), large light absorption coefficient, bipolar charge transport, and low-cost processing technology [1–8]. The above-mentioned good properties render perovskite materials very suitable for advanced photoelectric applications, especially in solar cells, photodetectors, light-emitting devices, photocatalysis [4, 9–13]. However, the lead toxicity and disappointing stability faced by conventional perovskites are two major bottlenecks for their practical commercial plan. On the one hand, the heavy metal (Pb) is harmful to the environment and the human body due to its easy dissolution in water [2]. At present, the European Union regulates the use of harmful heavy metals (including Pb) in electronic equipment, and the utilization of Pb-related technologies is supposed to decrease from now on. What is more, the practical applications of perovskite-based optoelectronic components are hindered by their poor stability against ambient humidity/oxygen, ultraviolet (UV) light, and heat [10]. As a result, from the standpoint of environmental protection and commercialization, it is extremely sought after to look for candidates to replace Pb in perovskites with comparable optoelectronic characteristics.

Recently, displacing Pb by other low- or non-toxic materials, including Sn$^{2+}$, Ge$^{2+}$, Bi$^{3+}$, Sb$^{3+}$, and Cu$^{+}$-based halide perovskites, has been widely studied, which is in line with the development concept of
building an environmentally friendly society [14–18]. For example, Sn\(^{2+}\) is the most direct candidate for Pb because it has a cognate outermost electronic configuration (ns\(^2\)) and ionic radius to Pb\(^{2+}\) [14]. Unfortunately, Sn\(^{2+}\)-based perovskites are instability in air and are easily oxidized to Sn\(^{4+}\), limiting their practical application. Although Bi\(^{3+}\) and Sb\(^{3+}\)-based perovskites show outstanding environmental stability, but their PLQY is generally lower than Pb-based counterparts, which limits their scope of applications [15]. Among the lead-free perovskite materials that have been reported, lead-free copper-based halides have caused widespread attention due to their excellent environmental tolerance and good photovoltaic properties [19–21]. Hosono et al reported the synthesis of ternary copper-halides Cs\(_3\)CuJ\(_4\) single crystals with a high PLQY of 90\%, and a good air stability with no significant PLQY degradation over two months was demonstrated [22]. Tang’s group demonstrated high-quality K\(_2\)CuBr\(_3\) single crystals by hydrochloric acid assisted slow cooling method, and further realized the application of efficient x-ray scintillator [23]. Among the reported copper-based halides, A\(_2\)CuX\(_3\) (A = K, Rb, X = Br, Cl) is characterized by a deep blue emission, which can make up for the blank of perovskites in this wavelength range [24–27]. Although the synthesis and emission mechanisms of various copper-based halides have been reported, they are always investigated in the form of single crystals and powders. As we all know, high-quality films, especially for nanoscale grain sizes, are the key to achieving high-performance optoelectronic devices due to easy integration and high flexibility; but the synthesis of high performance copper-based halide films is still a difficulty because of their inherent low-dimensional structure characteristics [28]. Moreover, strategies for improving the character of such films are seriously inadequate at present. Therefore, the realization of high-quality copper-based halide films with high PLQY is worth exploring. K\(_2\)CuBr\(_3\), which has excellent photoelectric properties, provides a basis for the preparation of high-quality films due to its better solubility in polar solvents [24].

In this work, a novel additive strategy is proposed to prepare high-quality and deep-blue-emitting K\(_2\)CuBr\(_3\) nanocrystalline films by introducing poly(methyl methacrylate) (PMMA) into the anti-solvent. The incorporation of PMMA into the K\(_2\)CuBr\(_3\) films can effectively decrease the grain dimension and improve the crystallinity of K\(_2\)CuBr\(_3\) films, thus achieving an enhanced radiation recombination through defect passivation and strong confinement of excitons in the nanograins. By optimizing the concentration of PMMA, deep-blue-emitting K\(_2\)CuBr\(_3\) films were obtained with the color coordinates at (0.156, 0.042) and a high PLQY of 21.2\%. Moreover, the PMMA-treated K\(_2\)CuBr\(_3\) films show an improved stability, retaining over 70\% of their initial emission performances in high humidity environment (50\%–70\% humidity, 190 h) or under uninterrupted UV light exposure (254 nm, 3.4 mW cm\(^{-2}\), 150 h). It could be expected that this study offers a promising strategy for the preparation of high-quality copper-based halide films and promotes their applications in optoelectronic fields.

2. Experimental section

2.1. Materials

KBr (99.98\%), CuBr (99.98\%) and PMMA were purchased from Sigma Aldrich. Dimethyl sulfoxide (DMSO), and methylbenzene (MB) were purchased from Beijing Chemical Reagent Co., Ltd, China.

2.2. Synthesis of K\(_2\)CuBr\(_3\) films

Preparation of precursor solution: The K\(_2\)CuBr\(_3\) precursor (0.4 mol\ l\(^{-1}\)) was prepared by weighing 2:1 molar ratio of KBr to CuBr in 5 ml vial and adding an appropriate amount of DMSO. After the vial is sealed, the blends were stirred at 70 °C in the normal environment until completely dissolved. Finally, the crude solution was filtered with a polytetrafluoroethylene filter (0.45 \(\mu\)m) in argon-filled glove box to obtain a black precursor solution.

Preparation of anti-solvent: PMMA was dissolved in MB as anti-solvent in different mass fractions.

Treatment of glass substrate: The glass substrates were ultrasonically cleaned by indium tin oxide abluer diluted with ultra-pure water and then dried by hair dryer. The substrates were further rinsed with UV–Ozone cleaner for 25 min.

Preparation of K\(_2\)CuBr\(_3\) films: K\(_2\)CuBr\(_3\) precursor solution (0.4 mol\ l\(^{-1}\)) was spin-coated on glass substrate by setting a low speed of 500 rpm (5 s) and a high speed of 2500 rpm (55 s). During the second spin-coating process (30 s), the anti-solvent (MB or MB–PMMA) was rapidly injected into the substrate to assist films formation. The samples were then transferred to a heating stage and annealed at 100 °C for 30 min. All samples were aged in normal environment for 1 h before use.

2.3. Characteristics

The crystallinity and phase purity of K\(_2\)CuBr\(_3\) films were characterized by x-ray diffraction (XRD). Atomic force microscopy (AFM) and SEM was used to analyze the morphology of the products. The surface roughness of K\(_2\)CuBr\(_3\) film is measured by AFM. The optical properties of K\(_2\)CuBr\(_3\) films, including
Figure 1. Processing procedures for the preparation of K$_2$CuBr$_3$ films. The insets show images of the chemical construction of PMMA (middle) and the crystal structure of K$_2$CuBr$_3$ (upper right).

absorption, steady-state PL, transient-state PL and temperature-dependent PL, were measured by UV–visible spectrophotometer (Shimadzu UV-3150) and dual grating fluorescence spectrometer (Horiba; Fluorolog-3, FluoroMax-4). The absolute PLQY of the K$_2$CuBr$_3$ films was measured by using a fluorescence spectrometer with an integrated sphere (Horiba; Quanta-ϕ).

3. Results and discussion

In this experiment, the K$_2$CuBr$_3$ films were synthesized by anti-solvent method, as reported in Pb-based perovskites [17], and the corresponding processing procedures are presented in figure 1. First, the dark precursor solution was spin-coated evenly onto the glass substrate. Then, during the spin-coating process, the anti-solvent (MB or MB-PMMA) was quickly dropped onto the substrate to assist in films formation. Finally, the resulting films are annealed at 100 °C for 30 min to evaporate the remaining solvent to improve the crystallization. The target product K$_2$CuBr$_3$ has a one-dimensional (1D) crystal structure; each [CuBr$_4$]$^{3−}$ tetrahedron and two adjacent [CuBr$_4$]$^{3−}$ shared angles form an infinite 1D chain. The chain structure is separated by K$^+$ atoms, as illustrated in upper right panes of figure 1 [29]. Such 1D crystal structure makes the nucleation and growth of crystal grains easy to follow the chain-like direction. With the goal of obtaining high-quality films with a densely packed morphology, we herein proposed a strategy of introducing polymer PMMA additives into the anti-solvent to assist the growth of grains. Although PMMA as a moisture barrier has been widely introduced into lead-halide perovskites devices, it is rarely used to affect the formation of perovskite itself during the solution processing. In our experiment, various concentrations of PMMA were added into the MB anti-solvent, as described in the section 2, and K$_2$CuBr$_3$ films were finally obtained by solution spin-coating method.

To investigate the effects of different concentrations of PMMA (0, 0.1, 0.3 and 0.5 wt%) on the morphology of K$_2$CuBr$_3$ films, SEM and AFM measurements were adopted. As exhibited in figure 2(a), the control sample (without PMMA) presents a bad morphology with a low surface coverage and an uneven aggregation of grains. However, the introduction of PMMA additive can substantially improve the surface coverage of K$_2$CuBr$_3$ films, showing decreased grain size and increased distributed density of grains, as displayed in figure 2(b). When the PMMA concentration increases to 0.3 wt%, the treated films show a more compact and smooth morphology (figure 2(c)), and the average grain size is greatly reduced from ~654.3 nm to ~96.7 nm compared with the control sample. Note that the average grain sizes of K$_2$CuBr$_3$ films are obtained by using Nano Measure Software, and the statistical histograms are shown in figure 2(i). One can clearly observe that the PMMA-treated (0.3 wt%) sample has the smallest grain size. This is a good
Figure 2. (a)–(d) SEM, and (e)–(h) AFM images of the $K_2CuBr_3$ films prepared by using different concentrations of PMMA in MB solution as anti-solvent. From left to right: without PMMA, 0.1, 0.3 and 0.5 wt% PMMA (SEM bar: 200 nm, AFM bar: 500 nm). (i) Statistical diagram of grain size, (j) average grain size and roughness, and (k) XRD patterns of four samples.

thing for luminescent materials because a reduced grain size with an increased distributed density implies an enhanced exciton confinement, thus an increased PLQY can be expected [30].

Meanwhile, the root-mean-square roughness (RMS) of the $K_2CuBr_3$ films were extracted from the AFM images. Figures 2(e)–(h) show the corresponding AFM images of four $K_2CuBr_3$ films samples, and the measured RMS values were plotted in figure 2(j). One can see that the RMS value of the PMMA-treated (0.3 wt%) sample is about 13.8 nm, which is much lower than that of the control sample (69.9 nm). There is no doubt that a flatter films surface is advantageous for constructing multilayer devices. While, further increasing the amount of PMMA to 0.5 wt% and 1.0 wt%, the morphology of $K_2CuBr_3$ films began to deteriorate, and the grain phase morphology changed from aggregation to decentralization with uneven grain size, as shown in figure 2(d) and figure S1 (supporting information (available online at stacks.iop.org/JPHOTON/4/014001/mmedia)), and a relatively large RMS value of 40.05 nm was observed (figure 2(h), 0.5 wt%). This suggests that excessive PMMA additive has the disadvantage of inducing in-situ nucleation, growth and heterogeneous crystallization of $K_2CuBr_3$ grains. Specifically, when the PMMA concentration exceeds a certain limit, the PMMA located at the grain boundary and the surface of the grains appears as a new phase, forming a visible thin film, which induces a retarded solvent evaporation. On the whole, the improved surface coverage, reduced grain size, and decreased surface roughness together confirm the positive effect of PMMA treatment on the morphology quality of $K_2CuBr_3$ films, suggesting their application potentials for optoelectronic applications. In order to verify whether the addition of PMMA will change the composition and crystallinity of the products, XRD measurements were further performed. As shown in figure 2(k), four samples exhibit the similar diffraction signals with 2θ peaks at 13.48°, 14.20°, 15.21°, 30.59° and 31.55°, corresponding to the (020), (200), (120), (240), and (420) crystal planes of orthorhombic $K_2CuBr_3$ (PDF #29-0997; space group, Pnma) [23]. The above results suggest that the introduction of PMMA will not deteriorate the $K_2CuBr_3$ phase, and no other impurity peaks (e.g. KBr, CuBr) emerge. By contrast, the sample with a PMMA additive of 0.3 wt% shows the strongest diffractions, as shown in figure 2(k), verifying a better crystallinity, and the reflected trends match well with the morphological evolution.

Further, we explored the optical characteristics of the $K_2CuBr_3$ films with different PMMA concentrations through absorption and steady-state PL spectrum characterization. As depicted in figure 3(a), four samples possess analogous deep-blue emission at $\sim$385 nm, and an obvious absorption peak at $\sim$285 nm was detected. All $K_2CuBr_3$ films exhibit a large Stokes shift ($\sim$100 nm) and wide full-width at half-maximum (FWHM) ($\sim$55 nm), similar to other low-dimensional metal-halide materials [17]. The broadband emission and large Stokes shift features could be interpreted by the excited-state structural
Figure 3. (a) UV–visible absorption spectra (left) and PL spectra (right) of K$_2$CuBr$_3$ films prepared with different conditions. (b) Photographs of different films under sunlight (bottom) and 254 nm UV light irradiation (upper). (c) Diagram for the self-trapped excitons dynamic mechanisms of the K$_2$CuBr$_3$ films. (d) CIE color coordinates of the K$_2$CuBr$_3$ films. (e) Time-resolved PL decay of four samples. (f) Statistical PLQYs and average PL lifetime of four samples.

reorganization or exciton self-trapping caused by Jahn–Teller distortion [18]. Therefore, we consider that the self-trapped excitons (STEs)-related recombination process leads to the deep-blue emission of K$_2$CuBr$_3$, as described in figure 3(c), and the relevant photophysical model can be summarized as follows: under the light excitation, the electrons in the valence band of K$_2$CuBr$_3$ can transition to the ground state to an excitation state manifold. Upon relaxation, the free electrons would ultrafast fall into the lower energy STEs states through the excited state structural reorganization. Finally, the recombination of electrons located in the STEs with holes occurs, resulting in a broadband blue emission with a large Stokes shift [18].

Notably, we observe that the PL intensity of PMMA-treated sample (0.3 wt%) is significantly increased by nearly two times compared to the control sample. Figure 3(b) exhibits the optical pictures of four samples under 254 nm UV light, visually showing the evolution of emission intensity. The Commission International de l’Eclairage (CIE) coordinates of such blue emission were calculated to be (0.156, 0.042), as shown in figure 3(d), fulfilling well with the strict Rec. 2020 blue standard [31], suggesting the potential of K$_2$CuBr$_3$ as a deep-blue light emitter. Moreover, we performed the transient-state PL measurements to examine the influence of PMMA additives on the carrier recombination dynamics of K$_2$CuBr$_3$ films. The PL decay curves of all films can be well fitted by a biexponential equation: $I(t) = I_0 + A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$, as exhibited in figure 3(e) [32]. The average lifetimes ($\tau_{\text{ave}}$) of four samples are calculated according to the following equation [32]: $\tau_{\text{ave}} = (A_1\tau_1^2 + A_2\tau_2^2)/(A_1\tau_1 + A_2\tau_2)$ and the fitted results are depicted in the dotted line of figure 3(f). One can observe that the PMMA-treated (0.3 wt%) films show a longer $\tau_{\text{ave}}$ of 32.45 $\mu$s than that of the control sample (7.55 $\mu$s). Generally, the increased $\tau_{\text{ave}}$ can be ascribed to the reduce of trap state density, thus the efficient usage of excitons is ensured. In other words, the $\tau_{\text{ave}}$ is inversely proportional to the trap state density, where longer $\tau_{\text{ave}}$ is correlated with less trap states [33]. The evolution trend of $\tau_{\text{ave}}$ is well consistent with the emission color change of K$_2$CuBr$_3$ films shown in figure 3(b). As a result, the PLQY of K$_2$CuBr$_3$ films was substantially increased for the PMMA-treated sample, which reaches a maximum value of 21.2% at a critical concentration (0.3 wt%), as presented in figure 3(f). The enhanced emission properties of K$_2$CuBr$_3$ films were primarily due to the suppressed non-radiative processes of carriers by the PMMA treatment. All these results above clearly reveal the improved luminescence quality of K$_2$CuBr$_3$ films assisted by PMMA additive engineering.

To better explain the enhanced emission properties of K$_2$CuBr$_3$ films after PMMA treatment, temperature-dependent PL measurement was carried out in the temperature range of 80–300 K, in which the K$_2$CuBr$_3$ sample with PMMA additive of 0.3 wt% was used for comparison. Figures 4(a)–(d) show the pseudocolor maps of temperature-dependent PL spectra of K$_2$CuBr$_3$ films without and with PMMA treatment. One could notice that the PL intensity of both samples shows a diminishing trend with increasing temperature caused by the thermally induced non-radiative recombination [34]. By contrast, the latter has a relatively slower temperature quenching behavior, which is presumably related with the reduced nonradiative
recombination paths in PMMA-treated sample (0.3 wt%). Figures 4(b)–(e) show the Arrhenius plots of the integrated PL intensity of two samples, and the temperature quenching behavior can be fitted by the following equation formula [35]:

$$I(T) = \frac{I_0}{1 + A \exp \left( -\frac{E_b}{k_b T} \right)}$$

(1)

where $k_b$ is the Boltzmann constant, $A$ is a proportional constant, $I_0$ is the emission intensity (0 K) and $E_b$ is the activation energy required for excitons (electron–hole pairs) to be split into free carriers or to be annihilated by non-radiative trap states. Generally, a higher $E_b$ can avoid the dissociation of excitons by thermal disturbance energy (26 meV) and achieve a high carrier recombination efficiency. In addition, even in a high-temperature environment, exciton emission can still exist efficiently. The fitting results show a value of $E_b = 139.4 \pm 7.9$ meV for the treated K$_2$CuBr$_3$ films, higher than that of the control sample ($113.6 \pm 0.5$ meV), as shown in figures 4(b)–(e). The higher $E_b$ of PMMA-treated K$_2$CuBr$_3$ films may result from an enhanced quantum confinement induced by grain size reduction, as observed in lead-based perovskite nanostructures [36]. Such a higher $E_b$ in PMMA-treated films favors an efficient radiative recombination and leads to a brighter blue emission, which is consistent with the changing trends of PLQY and PL decay discussed above.

Moreover, in order to explore the influence of exciton–phonon interaction in the carrier recombination process of K$_2$CuBr$_3$, the linewidth broadening behavior of the emission peak was studied. Figures 4(b)–(e) shown the temperature-dependent FWHM values of the emission, which were fitted by using the function [37]:

$$\text{FWHM}(T) = 2.36 \sqrt{S} \hbar \omega_{\text{phonon}} \sqrt{\coth \frac{\hbar \omega_{\text{phonon}}}{2k_b T}}.$$  

(2)

By fitting the temperature-related FWHM curve, the Huang–Rhys factor ($S$) of the control and treated samples was calculated as 34.93 and 33.06, and the phonon frequency ($\hbar \omega_{\text{phonon}}$) was calculated as 21.57 and 20.98 meV, respectively. The $S$ factor obtained is much higher than many traditional semiconductor
Figure 5. PL spectra evolution of the K$_2$CuBr$_3$ films with (upper) and without (bottom) PMMA treatment under (a) high humidity environment (50%–70%), and (c) persistent 254 nm UV light exposure (3.4 mW cm$^{-2}$). PL intensity evolution of two samples under (b) humidity aging process, and (d) continuous UV light irradiation.

materials with intrinsic emission characteristics, indicating a strong electron–phonon coupling in K$_2$CuBr$_3$ films, which facilitates the formation of STEs. The little change of $S$ factor suggests that PMMA additives does not affect the emission mechanisms of K$_2$CuBr$_3$. In addition, the slight reduction of $\hbar\omega_{\text{photon}}$ after PMMA treatment implies that the excitions are less affected by the lattice vibration [38]. Based on the experimental discussions as discussed before, the possible mechanisms for an enhanced carrier recombination in PMMA-treated K$_2$CuBr$_3$ films can be described by the schematic illustrations shown in figures 4(c)–(f). Before treatment, the defect states are likely to exist in large crystal grains and trap the photo-generated carriers, which will adversely affect the carrier recombination process (figure 4(c)). However, after the PMMA additive is incorporated for K$_2$CuBr$_3$ growth, a reduced grain size and desired surface passivation effect by PMMA could effectively suppress the nonradiative recombination paths of photo-generated carriers, and the defect-mediated nonradiative recombination can be inhibited. That is to say, the excited electrons trapped by the defects was limited, hence valid utilization of the excited carriers is promoted. As a result, the PLQY and PL lifetime are significantly enhanced (figure 4(f)).

It is worth noteworthy that the stability of Pb-based perovskites is the one of hinderings influencing their applications [39]. In our work, the environmental stability of the PMMA-treated K$_2$CuBr$_3$ films under different aging conditions was investigated by comparing with the control sample. First, the moisture stability test was performed at a high humidity condition (50%–70%) without encapsulation, and the PL spectra were continuously monitored in the process of aging test. As exhibited in figures 5(a) and (b), the spectral intensity of the control sample gradually decreased with increasing temperature, exhibiting a large emission degradation of 50% over 190 h aging test. While, for the K$_2$CuBr$_3$ sample with PMMA treatment, the emission intensity can maintain over 80% of the initial level after the same aging test. The improved moisture stability of K$_2$CuBr$_3$ films can be attributed to the hydrophobic PMMA additive, which provides a moisture barrier on the films [40]. In addition, we evaluated the photostability of K$_2$CuBr$_3$ films by continuously illuminating the samples with a 254 nm UV lamp (3.4 mW cm$^{-2}$). As shown in figure 5(c), an emission decay of 25% was detected for the PMMA-treated samples after a photostability test for 150 h, which is presumably aroused by the photo-oxidation reaction [23, 41]. By comparison, the control sample exhibits a rapid emission degradation, and a relatively large decay of 60% was generated. It is noteworthy that the peak position and spectral shape of the PL spectra maintained almost unchanged over the entire test. The results obtained show that, as a protective layer, PMMA could provide physical isolation to protect the K$_2$CuBr$_3$ films directly contacting high humidity and intense UV light, resulting in an improved environment stability. The above consequences demonstrate the robust stability of the K$_2$CuBr$_3$ films after
PMMA treatment, and are also evident of the reliable K$_2$CuBr$_3$ films with deep-blue emission and deep-UV absorption compatible for practical optoelectronic domain even in harsh conditions.

4. Conclusion
In conclusion, we have successfully prepared highly crystallized and densely packed K$_2$CuBr$_3$ nanocrystalline films with deep-blue emission feature by a polymer (PMMA) additive engineering strategy. The incorporation of PMMA into the K$_2$CuBr$_3$ films can not only effectively reduce the grain dimension but also improve the crystallinity of K$_2$CuBr$_3$ films, thus achieving an enhanced radiation recombinination through defect passivation and strong confinement of excitons in the nanograins. As a result, the PLQY obtained for the PMMA-treated K$_2$CuBr$_3$ films is about 3.3 times that of the pristine sample. Moreover, the PMMA-treated K$_2$CuBr$_3$ films demonstrated a substantially improved stability, preserving over 70% of their initial emission performances in high humidity environment (50%–70% humidity, 190 h) or under persistent 254 nm UV light exposure (3.4 mW cm$^{-2}$, 150 h). The results obtained prove that the proposed strategy, PMMA additive engineering, is beneficial to improve the emission performance and material stability of K$_2$CuBr$_3$ films. Moreover, the simple synthesis strategy endows the prepared K$_2$CuBr$_3$ films with a good reproducibility, but further use of them in optoelectronic devices requires more efforts in the future.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

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