Synthesis of Cs$_3$MnBr$_5$ Green Phosphors Using an Eco-Friendly Evaporative Crystallization Process

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ABSTRACT: Green (G) and red (R) light-emitting materials, such as quantum dots, perovskite nanocrystals, and inorganic phosphor powders, owing to their excellent optical characteristics, have attracted researchers’ attention as color-conversion materials for lighting and display applications. However, these materials contain environmentally harmful elements, such as Pb or Cd, and/or they are synthesized using environmentally harmful synthetic approaches and conditions, involving the use of organic solvents, high pressure, high temperature, harsh atmosphere, and long reaction time. In this study, as an eco-friendly synthetic approach to synthesize lead-free Cs$_3$MnBr$_5$ powder phosphor, we suggest an evaporative crystallization process of aqueous reactant solution. This synthetic process does not use toxic elements or solvents and the crystallization process utilizes only low reaction temperature and short reaction time under air atmosphere conditions. We successfully synthesized Cs$_3$MnBr$_5$ green powder phosphor, with excellent optical properties, by evaporative heating of a 200 nm syringe-filtered solution at 150 °C for 2 h.

The synthesized Cs$_3$MnBr$_5$ phosphors have a photoluminescence quantum yield of 66.3%, a peak wavelength of 520 nm, a narrow bandwidth of 38 nm, and a photoluminescence decay time of 0.34 ms under blue excitation. This phosphor is expected to be a useful alternative G-emitting material that can compete with commercial green quantum dots, perovskite nanocrystals, or inorganic phosphors.

1. INTRODUCTION

During the last decade, highly efficient, narrow-band cesium lead halide perovskite CsPbX$_3$ (X: Cl, Br, I) nanocrystals (NCs) have been actively developed for use as red, green, and blue (RGB) emitters in backlight films of liquid crystal displays, as color-conversion layers in color-by-blue display devices, and as emitting layers of perovskite NC light-emitting diodes (PLEDs). When these materials are used in display applications, their tunable peak position and narrow full width at half-maximum (fwhm) of the emission peak can be used to realize wide color gamut and high color purity. However, it is difficult to develop lead-free perovskite NCs or phosphors with appropriate peak position, narrow fwhm, and high photoluminescence (PL) quantum yield (PLQY).

Previously, because they have narrow fwhm of green emission peaks, Mn$^{2+}$-doped inorganic phosphors have been explored for application as backlights of liquid crystal displays. For example, γ-AlON/Mn$^{2+}$, Mg$^{2+}$, and MgAl$_2$O$_4$/Mn$^{2+}$ exhibit fwhm values of 44 and 35 nm, respectively. Furthermore, the fwhm value of Sr$_2$MgAl$_2$O$_6$·Mn$^{2+}$ phosphor can be as low as 26 nm and that of ZnAl$_2$O$_4$/Mn$^{2+}$ can be as low as 18 nm. Although Mn-doped phosphors achieve narrow fwhm of the green emission peak, the parity-forbidden property of low-concentration-doped Mn activators leads to relatively low absorption and long PL decay time. Therefore, it is necessary to develop eco-friendly Mn-emitting G phosphors with good peak position, narrow-band fwhm, relatively high doping level, and relatively short PL decay time.

Fortunately, recently developed zero-dimensional (0D) metal halides provide longer distance between Mn$^{2+}$ ions, which enables spontaneous emission with narrow-band G, R color. In addition, these materials also have relatively fast PL decay time, from a few nanoseconds to a hundred microseconds, making them appropriate for display applications. The d–d transitions of Mn$^{2+}$ ions in isolated tetrahedral and octahedral crystal fields are the sources of the pure G and R emissions, respectively. In an earlier research, organic–inorganic 0D Mn$^{2+}$-based halides were reported as excellent candidates for narrow-band green emitters, with high PLQY and fast decay time. However, the poor environmental stability of their organic-based composition limits their use in display applications. Recently, other groups have suggested the development of all-inorganic Mn$^{2+}$-based halides to form narrow-band G, R emitters for color-by-blue display applications, such materials have relatively high PLQY,

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excellent stability, and relatively short radiative PL decay times. In this regard, quite recently, cesium manganese(II) halide NCs and phosphors have attracted researchers’ attention for use as eco-friendly G, R emitters with strong PL. Among various inorganic cesium manganese(II) halide phosphors, Cs$_3$MnBr$_5$ NCs and/or phosphors are promising G emitters to replace both transition metal Mn$^{2+}$-activated green phosphors and CsPbBr$_3$ NCs.

Cs$_3$MnBr$_5$ NCs and powder phosphors have been reported to show a strong green emission peak at 520 nm, with a narrow fwhm of 39–43 nm and a fast PL decay time of 290 $\mu$s. So far, the maximum PLQYs of Cs$_3$MnBr$_5$ powder phosphors and NCs have reached 74.9$^{17}$ and 48%$^{18}$ respectively. As summarized in Table 1, both Cs$_3$MnBr$_5$ G and CsMnBr$_3$ R powders are synthesized using various crystallization approaches, such as HBr solution-based evaporative crystallization,$^{16}$ lyophilization-assisted recrystallization (LARC),$^{17}$ and a mechano-solid state reaction.$^{20}$ Cs$_3$MnBr$_5$ and CsMnBr$_3$ NCs are commonly synthesized using a hot-injection process.$^{16,19,21}$

Except for LARC, most synthetic methods use environmentally harmful organic solvents. Although LARC is an eco-friendly approach, it requires a low-temperature freezer and long reaction time for the solid-to-gas phase transition.$^{17}$ After purifying the reactant (MnBr$_2$ and CsBr) solution using a silicon nitride (SiN$_x$) membrane nanofilter, we reported the synthesis of Cs$_3$MnBr$_5$ G phosphors using the evaporative crystallization process without any environmentally harmful materials such as organic solvents or acids. We reported PLQYs of Cs$_3$MnBr$_5$ green phosphors up to 53%.$^{22}$ However, our previous report did not focus on evaporative crystallization for Cs$_3$MnBr$_5$ G phosphors, but mainly on the fabrication of the SiN$_x$ membrane nanofilter and the ultrafiltration process.

We introduced Cs$_3$MnBr$_5$ phosphor synthesis only as a good example of ultrafiltration by the SiN$_x$ membrane nanofilter. It is thus necessary to study the degree to which the purification process involving eco-friendly synthetic route of liquid-to-solid crystallization of aqueous reactant solution improves the purity, crystallization, and PLQY value of lead-free Cs$_3$MnBr$_5$ G phosphors. Furthermore, while performing evaporative crystallization processes, it is necessary to investigate the effects of various synthetic variables, such as reaction temperature, reaction time, and composition ratio, on the crystallization processes of Cs$_3$MnBr$_5$ green phosphors. In this study, using pre-purification of reactant solutions and optimization of synthetic variables, we have attained bright Cs$_3$MnBr$_5$ powder phosphors with a PLQY of 66.3%, a peak wavelength of 520 nm, and a fwhm of 38 nm by the evaporative crystallization process. The synthesis of Cs$_3$MnBr$_5$ phosphors starts with purification of the aqueous reactant solution. Undissolved ultrasmall-sized impurities are filtered using polyvinylidene difluoride (PVDF) syringes with pore sizes of 200 nm. Then, to obtain high-purity and crystalline Cs$_3$MnBr$_5$ powder phosphors, the filtered solution is crystallized using phase transformation of liquid-to-solid. In this study, bright and lead-free Cs$_3$MnBr$_5$ G phosphor can be obtained using an eco-friendly water-based evaporative crystallization process with relatively low reaction temperature and short reaction time. Our successful development and detailed study of this eco-friendly synthetic route proves its potential to produce bright, lead-free, and narrow-band Cs$_3$MnBr$_5$ G phosphors for display applications.

2. RESULTS AND DISCUSSION

Cs$_3$MnBr$_5$ G phosphors are synthesized by heating an aqueous reactant solution of MnBr$_2$ and CsBr at a reaction temperature...
below 200 °C through evaporative crystallization, as shown in
the schematic diagram in Figure 1. To optimize the synthetic
variables and select the best reactant materials, we assess the
PLQY of the as-synthesized Cs$_3$MnBr$_5$ powder phosphors.

Figure 2a compares the emission spectra of Cs$_3$MnBr$_5$ powders
as synthesized under the various filtration conditions, which
include non-filtration, paper filtration, and PVDF syringe
filtration with pore sizes of 200 and 450 nm. When MnBr$_2$

is dissolved in distilled water, an environment in which
manganese oxide or manganese hydroxide impurities may
form can be created. It is necessary to filter the reactant
solution to reduce undissolved impurities, including oxygen
impurities. Therefore, the PLQY of the synthesized Cs$_3$MnBr$_5$
phosphor increased as the filtration size became smaller, as
shown in Figure 2b. Furthermore, the crystallinity of the
Cs$_3$MnBr$_5$ phosphor obtained using the 200 nm filter was
better than that obtained when not using any filter. During the
purification step, we remove unnecessary impurity residue
from aqueous reactant solutions before evaporative crystal-
lization of Cs$_3$MnBr$_5$ powder phosphors.

After removing impurities from the two mixed reactant
solutions, the PLQY of the purified and heat-treated Cs$_3$MnBr$_5$
powder phosphors increases from 35% for the non-filtered
material to 66.3% after filtering using the 200 nm PVDF
syringe filter. As expected, the smaller the pore size of the
syringe filter used, the better the obtained PLQY (Figure 2b).

These results also confirm that impurities do not change the luminescence mechanism, but simply increase the non-radiative recombination, thereby reducing PLQY. The color coordinate values ($x = 0.199$ and $y = 0.728$) of the strongest PL emission spectrum indicate that Cs$_3$MnBr$_5$ powder phosphor has excellent G color and high color purity for display applications, comparable to those of previously reported Mn$^{2+}$-activated metal oxide phosphors.

Figure 2d shows that the PL excitation (PLE) spectra are well
matched with those of previously reported Cs$_3$MnBr$_5$ powder
phosphors. These PLE spectra are also monitored at
emission levels of 520 nm. All PLE spectra show three similar
bands at 280, 365, and 466 nm, which originate from the
different levels of energy splitting of $^4T_1$ excited state under the
tetrahedrally coordinated environment in the Cs$_3$MnBr$_5$ crystal
structure. As shown in Figure S2, the narrow-band and green
emission peak wavelength at 520 nm originates from the
excitation of the lowest state of $^4T_1$ to the ground state of $^6A_1$. Normalized PLE spectra of all four samples (Figure S1c)
also have identical shapes and similar levels of intensity. The
intense bands of the main excitation peaks, centered at 280,
365, and 466 nm, correspond to three excitation processes of
the tetrahedrally coordinated Mn$^{2+}$ ion with d$^5$ configuration. The CIE color diagram (Figure 2c) shows that all filtered and non-filtered Cs$_3$MnBr$_5$ powders have similar color coordinate values, indicating that the impurity phases have little effect on the emission spectrum. The identical normalized PL emission spectra, peak positions (~520 nm), and fwhm’s (~38 nm) of the four Cs$_3$MnBr$_5$ powders also confirm that the radiative recombination processes had the same origin (Figure S1a,b). These results also confirm that impurities do not change the luminescence mechanism, but simply increase the non-radiative recombination, thereby reducing PLQY.

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25033
6A_1 \rightarrow ^4F \text{ (UV B)}, \quad 6A_1 \rightarrow ^4D \text{ (UV A)}, \quad \text{and} \quad 6A_1 \rightarrow ^4G \text{ (blue) transitions.}^{23,24}

These results indicate that Cs_3MnBr_5 powder phosphor can be excited by blue LED chips as well as UV A and UV B LED chips.

Figure S2 shows splitting energy levels and optical transitions for the tetrahedrally coordinated Mn^{2+} ion. The detailed light absorption, non-radiative relaxation, and green emission process of tetrahedrally coordinated Mn^{2+} ion in Cs_3MnBr_5 powder phosphors can be seen. Likewise, syringe-filter-purified Cs_3MnBr_5 phosphors can be used as good color-converting materials for color-by-blue and color-by-UV display applications. Figure 2e provides TRPL decay curves of the radiative emission bands at 520 nm obtained from non-filtered and 200 nm syringe-filtered samples. The TRPL decay curves of all samples can be fitted using a single exponential decay formula

\[ I(t) = I_0 + A \cdot \exp(-t/\tau) \]

where \( I(t) \) and \( I_0 \) are the intensities of PL emission at time \( t \) and \( t \gg \tau \), \( A \) is a constant, and \( \tau \) is the TRPL decay time for the exponential component. The PL lifetime of the Mn^{2+} d\rightarrow d transition is particularly sensitive to the Mn–Mn distance. This is an important factor determining the PL lifetime, which can range from nanoseconds to milliseconds. The elongated Mn–Mn distance can lead to a coupled vibronic state such as self-trapped excitation, which is the cause of long, microsecond-scale lifetime.\(^{19}\) The TRPL decay times for both types of non-filtered and filtered Cs_3MnBr_5 powder phosphors are 0.31 and 0.34 ms, respectively, found by fitting the decay curves using a single exponential equation, confirming the single recombination process of unique Mn^{2+} ion sites in the Cs_3MnBr_5 structure.\(^{14}\) Compared to the TRPL decay time in excited states of high PLQY filtered sample, TRPL decay time in excited states of low PLQY unfiltered powders were slightly faster due to decreased radiative decay channels in lower efficiency samples. After filtration, TRPL results of Cs_3MnBr_5 powder phosphors indicate that G emission leads to a slight prolongation of PL decay time after removal of impurities. Therefore, the long PL decay time of the Cs_3MnBr_5 phosphor is intrinsically due to the long distance of Mn–Mn ions; the longer PL decay time of the purified Cs_3MnBr_5 phosphor is due to the reduced non-radiative recombination process, achieved by reducing secondary phases and defects by filtration of impurities.

The photographs on the left-hand side of Figure 2f show as-synthesized powders of both non-filtered and filtered Cs_3MnBr_5 samples. The body color of the phosphor changes from dark yellowish for the non-filtered powder to bright greenish for the filtered powders. The disappearance of dark spots indicates the decreased impurities in the phosphors after filtration. Similarly, the photographs on the right-hand sides of Figures 2f and S3 show that a brighter green emitting light can be obtained under a 365 nm UV lamp from the better filtered powder phosphors.

Figure 3a compares X-ray diffraction (XRD) diffraction patterns of crystal structures of the as-synthesized Cs_3MnBr_5 powder phosphors obtained under various filtration conditions, and (d) EDS data of elemental oxygen remaining with Cs_3MnBr_5 phosphors for various filtration conditions.\(^{14}\)
certain impurities or secondary phases of Cs$_3$MnBr$_5$, MnBr$_2$, and unknown phases. XRD patterns having enhanced major peaks, indexed by (114), (213), and (204) planes of the 200 nm syringe-filtered Cs$_3$MnBr$_5$ phosphors, indicate that Cs$_3$MnBr$_5$ powder is better crystallized, with the tetragonal phase, than are unfiltered Cs$_3$MnBr$_5$ phosphors. However, small amounts of certain residual phases remain after the optimum evaporative crystallization process (at 150 ºC for 2
h) of the purified reactant solutions. In terms of improving the PLQY or crystal quality of the synthesized Cs$_3$MnBr$_5$ powder phosphors, it will be necessary to further remove remaining impurities via the pre-filtration process before evaporative crystallization.

The SEM photographs (Figure 3b) of the non-filtered Cs$_3$MnBr$_5$ powders and of all of the filtered Cs$_3$MnBr$_5$ powders show morphologies that are similar in shape and agglomerated into nano-sized fine particles. EDS mapping measurements (Figure 3c) also indicate that Cs, Mn, and Br are evenly distributed for all four Cs$_3$MnBr$_5$ powders. EDS data also indicate that the better-filtered phosphor powder exhibits a phase with small amounts of elemental oxygen remaining, as shown in Figure 3d. As can be seen in the insets of Figure 4a, the color of the purified aqueous reactant solution becomes increasingly transparent with increased filtering. The photographs indicate that the purification process works effectively using any of the filters. Figure 4a also shows that the impurity absorption spectrum of the filtered solution decreases as the filtering effect increases. Absorption peaks indicate that the majority of impurities are removed, but small amounts of impurities remain in the purified solution even after purification by the syringe filter with the smallest pores. The XRD patterns in Figure 4b show mixed powder patterns for filtered impurities obtained from the surface of the 200 nm syringe filter. The SEM images in Figure 4c show that the filtered impurities have irregular shapes of agglomerated micro- and nanoparticles, with average sizes larger than the pore size of the syringe filter. EDS elemental analysis results shown in Figure 4d indicate that impurities consist of Mn, Cs, Br, and O elements in powders separated from solutions. Because oxygen is also detected in very small amounts in the filtered solids, these impurities might be amorphous mixtures of Mn- and/or Cs-related oxides or hydroxides, as well as bromide, with average agglomerated size larger than the pore size of the syringe filter. $^{23}$ When a 200 nm syringe filter is used, oxygen impurities in the phosphor can be minimized.

We select the 200 nm syringe filter for purification of reactant solution for further optimization process. First, we optimize the optical quality of the as-synthesized Cs$_3$MnBr$_5$ powders by comparing the PLQYs and emission spectra of the as-synthesized Cs$_3$MnBr$_5$ powders as a function of evaporative temperature (Figure 5a,b). The resulting figures indicate that the best PLQY (66.3%) of Cs$_3$MnBr$_5$ powders is obtained by heating at 150 °C. Except for those of the Cs$_3$MnBr$_5$ powders synthesized at 110 °C, the PL spectrum and CIE color coordinates (Figure 5c) are almost identical in shape and position. XRD spectra also confirm that XRD patterns of the best PLQY Cs$_3$MnBr$_5$ powders are well matched with those of the standard Cs$_3$MnBr$_5$ phase (PDF card no. 71-1416, Figure 5c), with only minor impurity phases. Below 140 °C, with decreasing crystallization temperature, a phase transformation is observed from Cs$_3$MnBr$_5$ to mixed phases. This also indicates that crystal phases of powders are nearly identical in the crystallization temperature range of 150–190 °C.

Therefore, it is not easy to correlate the big changes of PLQY with the small peak changes found in the XRD patterns. It can be inferred that defects, which cannot be discerned by XRD and cause non-radiative recombination, greatly increase after the optimum evaporative temperature. As shown in Figure 5b,d, PLQY of the synthesized Cs$_3$MnBr$_5$ phosphors drops between 110 and 130 °C because Cs$_3$MnBr$_5$ phosphor crystals are not well formed. There is a correlation between the values of PLQY and fwhm of the (213) peak in the XRD...
patterns of Cs$_3$MnBr$_5$ phosphors, synthesized from 140 to 190 °C, as shown in Figure 56. The greater the increase of the PLQY of the synthesized Cs$_3$MnBr$_5$ phosphors, the greater the decrease of the fwhm of the XRD maximum intensity peak. Therefore, we have chosen the evaporative temperature of 150 °C, which leads to the best PLQY of Cs$_3$MnBr$_5$ phosphors synthesized as a function of evaporative temperature and filtered using a 200 nm syringe filter. At temperatures between 150 and 190 °C, the body colors of all phosphors are similarly bright greenish; the phosphors also all emit bright green light under UV excitation (Figure S4). XRD results also show that the temperature dependence of the body color and light emission is not as sensitive as the change of PLQY. In the next step, PLQY was optimized according to the change in reaction time at 150 °C. The PL spectrum, CIE color coordinates, and PLQY graph in Figures S5 show that the best PLQY and best spectrum are obtained by heating at 150 °C for 2 h.

As a third step, we investigate the effect of the atomic ratio of Mn to Cs elements on the luminescence properties of Cs$_3$Mn$_{x}$Br$_{3+2x}$ phosphor powders. Although there are differences in the intensity of the spectra, the position and fwhm of the PL spectra show almost identical values even with variation of the compositional ratio, as shown in Figure 6a. The CIE color coordinates also show almost identical coordinate values of emitted light for the different composition ratios (Figure 6b). This confirms that the emission spectrum of Cs$_3$Mn$_{x}$Br$_{3+2x}$ phosphor powders is not significantly affected by the composition ratio; however, PLQY changes very sensitively. Figure 6c shows that PLQY decreases when the composition ratio of Cs/Mn deviates from 3:1. The XRD patterns (Figure 6d) also show that secondary impurity peaks appear in the Cs$_3$Mn$_{x}$Br$_{3+2x}$ crystal phase for the off-stoichiometric composition. At composition ratios of 3:0.9 and 3:1.1, a shoulder appears for the longer 2θ of the (204) main peak, and a secondary impurity peak also appears at ratios of 3:1.2 or higher. These results reconfirm that PLQY increases as the composition approaches the pure tetragonal phase of stoichiometric Cs$_3$MnBr$_5$ crystal structure.

3. CONCLUSIONS
In conclusion, we successfully developed eco-friendly Cs$_3$MnBr$_5$ powder phosphor as a G color-converting material using evaporative crystallization based on aqueous solution, an eco-friendly crystallization process using non-toxic solvent. As with the optimization process of synthesizing conventional inorganic phosphors, it is shown that reducing impurities in raw materials and increasing crystallinity of phosphor powders are the most important factors to increase the PLQY of Cs$_3$MnBr$_5$ phosphor powder. The brightest Cs$_3$MnBr$_5$ phosphor powder was obtained in an evaporative crystallization process by filtering aqueous mixed reactant solution with a 200 nm syringe filter and heating the filtered solution at a low temperature of 150 °C for a short reaction time of 2 h. Synthesized Cs$_3$MnBr$_5$ had optical properties of a PLQY of 66.3%, a peak wavelength of 520 nm, an fwhm of 38 nm, a decay time of 0.34 ms, and CIE color coordinates x = 0.199 and y = 0.728. Even though efficient and crystallized Cs$_3$MnBr$_5$ powders were synthesized by pre-filtered evaporative crystallization, a small portion of unknown impurities remained in the reactant solution, reducing the PLQY. Therefore, if any additional advanced purification process is to be developed in the future, impurity particles smaller than the pore size of the syringe filter will have to be completely removed before crystallization. We suggest a simple method of synthesizing eco-friendly Cs$_3$MnBr$_5$ green phosphors through eco-friendly evaporative crystallization at low annealing temperature and short reaction time without using organic or acid solvents. In addition, we anticipate improved potential for realizing next-generation G light-emitting material for use in G color-converting layers in display applications.

4. METHODS

4.1. Materials. Cesium bromide (CsBr, 99.999%, Sigma-Aldrich), manganese(II) bromide (MnBr$_2$, 98%, Sigma-Aldrich), and distilled water.

4.2. Synthesis of Cs$_3$MnBr$_5$, Green Phosphors through Evaporative Crystallization. 0.09 mmol of CsBr, 0.03 mmol of MnBr$_2$, and distilled water were added to a beaker and heated and stirred at 60 °C for 30 min to ionize precursors. Then, the ionized reactant solution was filtered using various filtration conditions such as no filter, paper filter, a 450 nm syringe filter, and a 200 nm syringe filter to reduce impurities. The filtered ionized reactant solution was crystallized in a furnace at 150 °C for 2 h via evaporative crystallization. For further optimization, a 200 nm syringe filter for purification of reactant solution was synthesized as a function of crystallization temperature (110, 130, 140, 150, 160, 170, 190 °C) and via the Cs$_3$Mn$_{x}$Br$_{3+2x}$ molar ratio (x = 0.9, 1.0, 1.1, 1.2, 1.3) for 2 h.

4.3. Characterization. The absorbance of filtered solutions was measured with a UV−vis spectrometer (S-3100, SINCO Co., Ltd.) PL and PLE spectra of the synthesized Cs$_3$MnBr$_5$, green phosphors were obtained with an Xe lamp and spectrophotometer (Darsa, PSI Trading Co., Ltd.). PLQYs of the synthesized Cs$_3$MnBr$_5$ phosphors were measured in comparison with that of YAG:Ce$^{3+}$ phosphor (absolute PLQY = 0.95 at 450 nm), measured using a TCSPC spectrofluorometer (Fluorolog 3, HORIBA). The TRPL spectra were measured using a home-made spectrometer. The synthesized Cs$_3$MnBr$_5$ phosphors were excited by the third harmonic of a nanosecond laser (SL-20, Continuum) under ambient conditions. The emission was spectrally resolved using a monochromator, detected using a photomultiplier, and recorded using an oscilloscope (WAVE-SURFER 454, LeCroy). The crystal phases of the obtained Cs$_3$MnBr$_5$ green phosphors were characterized by XRD (Ultima IV, Rigaku). SEM (JSM-7610F, JEOL Ltd.) and EDS were utilized to analyze the size, morphology, crystal structure, elemental composition, and impurities of the synthesized Cs$_3$MnBr$_5$ green phosphors.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c00943.

Detailed optical properties and photographs and EDS data of the synthesized Cs$_3$MnBr$_5$ phosphors with various filtration conditions and various crystallization temperatures (PDF)

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