Ytterbium-Doped Cesium Lead Chloride Perovskite as an X-ray Scintillator with High Light Yield

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ABSTRACT: Ytterbium-doped cesium lead halides are quantum cutting materials with exceptionally high photoluminescence quantum yields, making them promising materials as scintillators. In this work, we report ytterbium-doped cesium lead chloride (Yb³⁺:CsPbCl₃) with an X-ray scintillation light yield of 102,000 photons/MeV at room temperature, which is brighter than the current state-of-the-art commercial scintillators. The high light yield was achieved based on a novel method of synthesizing Yb³⁺:CsPbCl₃ powders using water and low-temperature processing. The combination of high light yield and the simple and inexpensive manufacturing method reported in this work demonstrates the great potential of Yb³⁺:CsPbCl₃ for scintillation applications.

1. INTRODUCTION

Detection of X-ray photons is critically important in various fields, such as security, medical radiography, industrial manufacturing, and astronomy.¹⁻⁵ Scintillators play key roles in many of these applications by absorbing X-ray photons and emitting visible or near-infrared photons for detection with conventional photodetectors. However, the state-of-the-art commercial scintillators are manufactured using complex fabrication methods such as single-crystal growth at high temperature (∼1700 °C), which make their cost prohibitively high for applications that require large area detection.⁶,⁷ Alternatives such as plastic scintillators⁸⁻¹⁰ can be inexpensively manufactured into large dimensions at low temperature, but they are not commonly used in high-energy X-ray systems due to their low stopping power, low light yield, and poor energy resolution that do not meet the performance criteria.

Metal halide perovskites (MHPs) have recently been identified as promising scintillator materials.¹¹,¹² MHPs are low-band gap (1.6⁻₉ ² eV) materials composed of high-Z atoms with chemical composition of ABX₃, where A = Cs⁺, CH₃NH₃⁺, and so forth, B = Pb²⁺, Sn²⁺, and X = Cl⁻, Br⁻, and I⁻. With a combination of relatively high effective atomic number, high density, and low band gap, MHPs are efficient hard radiation absorbers with potential light yields as high as 250,000 photons/MeV.¹³⁻¹⁵ MHPs are composed of entirely earth abundant, low-cost elements, and can be synthesized into single crystals, polycrystalline powders, or thin films using simple solution processing methods at low temperatures (25⁻¹⁵₀ °C). Therefore, MHP-based scintillators are expected to be drastically cheaper compared to current commercial scintillators.¹⁶,¹⁷ Even in highly defective polycrystalline forms, MHPs exhibit low charge trapping due to defect tolerance.¹⁸,¹⁹ For this reason, charge carrier diffusion length can be as long as few microns in polycrystalline MHP powders synthesized at low temperature.²⁰ These attributes can be exploited to obtain high performance in optoelectronic devices such as solar cells and photodetectors.

However, pure MHP compositions by themselves have so far demonstrated limited scintillation performance due to the low exciton binding energy in MHPs, suppressing the formation of excitons and radiative recombination.¹²,²¹ To overcome this limitation, liquid nitrogen temperatures were required to obtain sufficient light yield.¹²,²¹ Formation of nanostructured MHPs into quantum dots or quantum wells to increase the exciton binding energy has shown to increase the light yield²²,²³ but at the expense of increased band gap and drastic cost increase associated with nanoparticle synthesis. Moreover, pure MHP composition scintillators suffer from the large overlap between photoluminescence and absorbance spectra which causes reabsorption of emitted photons.

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In this work, we sought to address all of the challenges mentioned above using ytterbium (Yb\(^{3+}\))-doped cesium lead chloride perovskites (Yb\(^{3+}\):CsPbCl\(_3\)) as scintillators. Doping of cesium lead halide (CsPbX\(_3\)) with Yb\(^{3+}\) can boost the photoluminescence quantum yield (PLQY) above 100% through the quantum cutting process\(^{24,32}\), wherein one photon absorbed by the CsPbX\(_3\) matrix can be converted into two photons emitted from the Yb\(^{3+}\) dopants. The bright emission through the quantum cutting process, combined with high atomic number compositions, makes Yb\(^{3+}\):CsPbCl\(_3\) compelling for scintillator applications, and yet, there has been no report on scintillation from Yb\(^{3+}\)-doped MHPs. In this paper, we report a novel method of synthesizing Yb\(^{3+}\):CsPbCl\(_3\) powders using only water as the solvent and mild thermal annealing (below 200 °C). Our manufacturing method can produce a large quantity of Yb\(^{3+}\):CsPbCl\(_3\) powder in a low-cost and scalable fashion. The Yb\(^{3+}\):CsPbCl\(_3\) powder can be sintered into any shape and size for various target applications. Radioluminescence activity was optimized as a function of Yb doping amount. The highest performance was achieved with 5 mol % Yb doping amount Yb\(^{3+}\):CsPbCl\(_3\) with light yield of 102,000 photons/MeV under room temperature operation, which is higher than light yields of state-of-the-art commercial scintillators. The Yb\(^{3+}\):CsPbCl\(_3\) powder was pressed into a pellet for radiographic imaging of various objects with a complementary metal-oxide-semiconductor photodetector. Our results demonstrate the promising potential of Yb\(^{3+}\):CsPbCl\(_3\) for scintillators that can simultaneously achieve high performance, large area detection, and low cost.

2. RESULTS AND DISCUSSION

The Yb\(^{3+}\):CsPbCl\(_3\) powder samples were prepared using simple solution processing with water as the solvent, as illustrated in Figure 1a. Stoichiometric amounts of cesium chloride (CsCl, water solubility 1910 g/L at 25 °C), lead chloride (PbCl\(_2\), water solubility 0.99 g/100 mL at 20 °C), and ytterbium chloride (YbCl\(_3\), water solubility 17 g/100 mL at 25 °C) precursors were combined in de-ionized water, stirred at 40 °C for 1 h, after which the water was removed through evaporation at 65 °C. The resultant powder was then finely crushed in a mortar and pestle and annealed at 200 °C for 1 h, with mechanical stirring and mixing during the process. Seven powder samples were produced with varying Yb\(^{3+}\) ion contents from 0.5 mol % up to 60 mol %.

The X-ray diffraction (XRD) patterns of the Yb\(^{3+}\):CsPbCl\(_3\) samples are shown in Figure 1b, along with a reference pattern of the orthorhombic structural phase (Pnma) of CsPbCl\(_3\). The XRD patterns from Yb\(^{3+}\):CsPbCl\(_3\) with less than 25% Yb\(^{3+}\) content match well to the CsPbCl\(_3\) reference pattern, in agreement with previous reports which show that Yb\(^{3+}\) doping at low concentrations retain the bulk CsPbCl\(_3\) crystal structure\(^{31}\). The orthorhombic (Pnma) structure of these powder samples is consistent with Yb\(^{3+}\):CsPbCl\(_3\) powders formed through the solid-state reaction\(^{32}\) and vapor deposition\(^{31}\) and is in contrast with the cubic (Pm3m) structure of Yb\(^{3+}\):CsPbCl\(_3\) nanocrystals and quantum dots\(^{29,33,35}\). The well-matched patterns between CsPbCl\(_3\) and Yb\(^{3+}\):CsPbCl\(_3\) at and below 5% Yb\(^{3+}\) content, without any presence of peaks from precursor materials and other possible phases, suggest that the Yb\(^{3+}\) ions are incorporated into the CsPbCl\(_3\) host lattice through placement into the Pb\(^{2+}\) sites. The (101) peak location at 2θ = 22.4° does not shift significantly as a function of Yb\(^{3+}\) amount, suggesting that the substitution of the smaller Yb\(^{3+}\) ion in the Pb\(^{2+}\) position does not result in any significant lattice compression. In the 25, 45, and 60% Yb\(^{3+}\):CsPbCl\(_3\) compositions, XRD peaks not matching to the CsPbCl\(_3\) structure are observed, indicating the presence of impurity species at these higher Yb\(^{3+}\) doping concentrations that reduce the orthorhombic crystallinity of the samples (Figure S1). The majority of the impurity phase in high (>25%) Yb amount samples is likely to be Cs\(_4\)PbCl\(_6\), as shown in Figure S2. These results show that our water-based and low-temperature synthesis method results in high purity Yb:CsPbCl\(_3\) with the Yb\(^{3+}\) dopants substituted into the Pb\(^{2+}\) sites in the lattice in Yb\(^{3+}\) concentrations at and below 5%.

The morphology of the 5% Yb\(^{3+}\):CsPbCl\(_3\) powder is shown in the SEM image in Figure 1c. The powder was found to be composed of micrometer scale grains. EDXS images show that...
the Cl\(^-\), Pb\(^{2+}\), Cs\(^+\), and Yb\(^{3+}\) are distributed throughout the entirety of the grains (Figures 1d–g, S3). Few areas of higher concentration of Cs\(^+\) and Yb\(^{3+}\) were observed (Figure 1f,g), which suggests that there are some regions of the samples with higher Yb\(^{3+}\) concentration. The average surface elemental composition of the 5% Yb\(^{3+}\):CsPbCl\(_3\) sample obtained through EDS shows that the Yb\(^{3+}\) doping amount is close to the stoichiometric amounts of the precursor used in the synthesis based on the measured Yb\(^{3+}\) to Pb\(^{2+}\) ratios (Table S1).

The absorbance and photoluminescence spectra of 5% Yb\(^{3+}\):CsPbCl\(_3\) sample are shown in Figure 2a. A spectrophotometer and a spectrofluorometer, both equipped with an integrating sphere, were employed for these measurements to account for any light scattering in the powder samples (see details in the Materials and Methods section). Our results show that there is a large Stokes shift between the absorption onset at 440 nm and the photoluminescence emission peak at 1000 nm. This is consistent with previous reports on Yb\(^{3+}\):CsPbCl\(_3\) wherein the light absorption occurs in the CsPbCl\(_3\) with the onset of 440 nm, and the emission peak at 1000 nm originates from the \(^{2}F_{5/2} \rightarrow ^{2}F_{7/2}\) transition in Yb\(^{3+}\) ions.\(^{27,29}\) The photoluminescence from the CsPbCl\(_3\) matrix at 406 nm is greatly suppressed as a result of efficient sensitization with the Yb\(^{3+}\)-ion dopants (inset in Figure 2a). The emission wavelength of 1000 nm is well-matched with silicon photodiodes that are cost effective and widely available for coupling with scintillators in various applications. Moreover, the large Stokes shift is advantageous for the scintillator performance as it prevents the re-absorption of radioluminescence photons by the material, enabling increased scintillator thickness without attenuating the emitted photon flux.\(^{38}\)

Radioluminescence spectra of the Yb\(^{3+}\):CsPbCl\(_3\) samples were measured using a spectrofluorometer equipped with a Moxtek MAGPRO X-ray source operating at 40 kV and 300 \(\mu\)A. To ensure consistent amounts of excited scintillator material and X-ray excitation conditions, all Yb\(^{3+}\):CsPbCl\(_3\) samples in the powder form were loaded into identical Kapton capillary tubes and placed into an integrating sphere with consistent sample placement (see the Materials and Methods section for the detailed experimental procedure). Our measurements show a trend of increasing radioluminescence intensity from Yb\(^{3+}\):CsPbCl\(_3\) samples with increasing Yb\(^{3+}\)-ion contents up to 5% (Figure 2b). This is consistent with previous papers that showed larger PLQYs in Yb\(^{3+}\)-doped CsPbX\(_3\) with more Yb\(^{3+}\) ions in the low Yb\(^{3+}\) concentration regime.\(^{27,29}\) Our results indicate that similar behavior occurs in radioluminescence emission as well. This is likely caused by more efficient sensitization of Yb\(^{3+}\) dopants due to larger number of Yb\(^{3+}\) defect complex sites and reduced average distances for...
charge carriers to travel. However, at above the 5% Yb\textsuperscript{3+} doping level, we observed the opposite trend of decreasing radioluminescence intensity with higher Yb\textsuperscript{3+} concentration (Figure 2c). We attribute this to presence of impurity species based on our XRD results (Figure 1b) that show an increased amount of impurity species with increasing Yb\textsuperscript{3+} ion content above 5%.

An important performance metric for scintillators is the light yield, which is defined to be the number of photons emitted per absorbed radiation energy. Given the same radiation source, scintillators with higher light yield produce brighter radioluminescence emission for more sensitive detection with photodetectors. In various applications, such as medical imaging and national security, sensitive detection of weaker intensity radiation is highly desired. The scintillation light yields of our Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} samples, as well as commercially available reference scintillators CaF\textsubscript{2}(Eu) and CsI(Tl), were quantified using excitation from the X-ray source operating at 40 kV and 300 μA (see the Materials and Methods section for details).

Consistent with the trend observed in the radioluminescence spectra intensity as a function of Yb\textsuperscript{3+} amount, we found that the 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} provided the highest performance with a light yield of 102,000 photons/MeV (Figure 3a). This is a significantly higher light yield than the state-of-the-art commercially available scintillators such as CsI(Tl) with a light yield of 65,000 photons/MeV (see Table S3 for comparison of light yields from various scintillators). The high light yield from Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} can be attributed to the combination of relatively low band gap of CsPbCl\textsubscript{3}, resulting in greater charge carrier generation with high energy radiation absorption, long charge carrier lifetime, and diffusion length even in polycrystalline samples\textsuperscript{23} and bright emission from the quantum cutting process.\textsuperscript{24–32} Previous studies in the context of downconverters for solar cells have found that Yb\textsuperscript{3+}-doped CsPbX\textsubscript{3} exhibits luminescence saturation at increasing photo-excitation fluences, limiting the emission of the material.\textsuperscript{25,29} To check whether our 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} sample is limited by the saturation effect, we measured the radioluminescence intensity as a function of excitation X-ray flux. As shown in Figure 3b, the photons emitted from the sample varies linearly with the X-ray source current, indicating that saturation does not occur within the operating conditions of the X-ray source employed in this study.

To demonstrate the applicability of our Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} for radiographic imaging, a cylindrical pellet of the 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} powder sample was manufactured by hydrostatic pressing the powder under 6 tons of pressure at 70 °C for 2 h while under vacuum at 70 °C. Images of various objects under X-ray irradiation formed on the scintillator pellet were captured using a Basler NIR GigE camera (Figure 3c,d). In Figure 3c, a thumbtack is shown, in which the embedded metal pin inside the plastic head is clearly visible. Figure 3d shows a micro-SIM phone card, in which the metal contact is differentiated from the plastic casing.

3. CONCLUSIONS

We have shown the first detection and application of radioluminescence in a Yb\textsuperscript{3+}-doped cesium lead halide perovskite. Our water-based synthesis method produces Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} powder over a wide composition range that shows incorporation of the Yb\textsuperscript{3+} dopant with high purity up to a maximum of 5 mol %. The water evaporation and low-temperature annealing method presented here is among the simplest methods of producing Yb\textsuperscript{3+}:CsPbX\textsubscript{3} but does not sacrifice the crystallinity of the CsPbCl\textsubscript{3} host lattice. The 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} sample has a large Stokes shift and the strong characteristic Yb\textsuperscript{3+} emission at 1000 nm. Suppressed CsPbCl\textsubscript{3} excitonic emission at 406 nm proves efficient transfer of charge carriers from the bulk lattice to the defect Yb\textsuperscript{3+} emission sites. Radioluminescence is exhibited by all Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} samples and is optimized at 5 mol % due to a balance of high Yb\textsuperscript{3+} ion content and high material purity. The champion 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} composition has a measured light yield of 102,000 photons/MeV, which is higher than those from the commercial scintillator options. Radiographic imaging was demonstrated using a pressed powder pellet.

4. MATERIALS AND METHODS

4.1. Synthesis of Yb\textsuperscript{3+-Doped CsPbCl\textsubscript{3}} Powder. Cesium iodide (CsI, >99.0%) was purchased from Tokyo Chemical Industry (TCI), lead(II) chloride (PbCl\textsubscript{2}, 99.999%) was purchased from Alfa Aesar, and ytterbium(III) chloride hexahydrate (YbCl\textsubscript{3}-6H\textsubscript{2}O, 99.9%-Yb) was purchased from STREM Chemicals. The precursors were combined according to the Yb\textsubscript{3+}:CsPbCl\textsubscript{3} stoichiometry, assuming 2Yb\textsuperscript{3+}:1VPb substitution at the Pb\textsuperscript{2+} B-sites, in Yb\textsuperscript{3+} molar percents of 0, 0.5, 1, 3, 5, 25, 45, and 60%. The precursors were dissolved in de-ionized water at a concentration of 5 g/L and stirred for 1 h at 40 °C. The solution was then transferred to a crystallization dish, and the water was slowly evaporated off at a temperature of 65 °C while stirring. The resultant powder was finely crushed using a mortar and pestle, transferred back to the crystallization dish, and annealed for 1 h at 200 °C, stirring four times during the annealing process. The pressed powder pellet of 5% Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} was fabricated using a 25 mm pellet die and an Atlas Manual Hydraulic Press under 6 tons of pressure for 2 h while under vacuum at 70 °C.

4.2. Physical Characterization. XRD patterns of the Yb\textsuperscript{3+}:CsPbCl\textsubscript{3} powders were measured using an Empyrean Multipurpose X-ray diffractometer with a Cu anode, at 45 kV and 40 mA with step size 0.02°. SEM and EDXS were measured on an FEI Quanta 650 Scanning Electron Microscope.

4.3. Optical Characterization. The steady-state photoluminescence spectra were measured using a PTI QuantaMaster 400 spectroradiometer, using a Xe arc lamp excitation source monochromated at a wavelength of 405 nm. The absorbance spectra were measured using a PerkinElmer UV/vis/NIR Lambda 950S spectrometer equipped with an integrating sphere.

4.4. Radioluminescence Characterization and Light Yield Calculation. 4.4.1. Materials. A Mixtek 60 kV 12 W MagPro X-ray imaging source was used for X-ray generation. Commercial scintillators CaF\textsubscript{2}(Eu) and CsI(Tl) were purchased from Epic-Crystal Co. with light yields of 19,000 and 60,000 ph/MeV, respectively. Both commercial scintillators were grown via the Bridgeman method and cut to be 25.4 × 25.4 × 25.4 mm\textsuperscript{3} cubes with all sides polished. An acrylic glass cube with dimensions 25.4 × 25.4 × 25.4 mm\textsuperscript{3} with all sides polished was purchased from U.S. Plastic Corporation. Power meters equipped with a silicon photodiode (PM16-120) and a germanium photodiode (PM16-122) were purchased from Thor Labs. A PTI QuantaMaster 400 spectroradiometer equipped with a UV–vis photomultiplier tube (PMT) (PFR Technologies, LLC, R2658) and NIR PMT (Hamamatsu
Photonics, H10330-75) was used to measure radioluminescence and reference light signals.

### 4.4.2. Approach
The light yield of the Yb$^{3+}$:CsPbCl$_3$, reported in photons per MeV of energy deposited, was determined in two parts. The energy deposited by the X-ray source was quantified using the known light yields of two commercial scintillators, CaF$_2$(Eu) and CsI(TI). The energy-deposited values were corrected for non-proportionality of CaF$_2$(Eu) and CsI(TI) at the specific keV X-ray energies produced by the X-ray source used in the measurement. To quantify the Yb$^{3+}$:CsPbCl$_3$ photon output, the power of a reference light source was correlated to the PMT detector response; correcting for spectral sensitivity of the detector at different wavelengths.

Radioluminescence signals were obtained for the commercial scintillators and the Yb$^{3+}$:CsPbCl$_3$ scintillators using the Moxtek 60 kV 12 W MagPro X-ray Imaging Source at 300 μA and 40 kV. All scintillators studied were placed inside an integrating sphere and arranged into two rows of six, which was confirmed to achieve total attenuation of X-rays.

#### 4.4.3. Powder Sample Preparation
Powder samples were packed into 12 Kapton capillaries purchased from Cole-Parmer (0.0710” ID, 0.0750” OD, cut to a length of 50 mm). Capillaries were sealed on both ends with Sigilum Wax sealant purchased from Thomas Scientific and arranged into two rows with the same geometry as the Yb$^{3+}$:CsPbCl$_3$ scintillators. Wavelengths matching the emission of commercial and Yb$^{3+}$:CsPbCl$_3$ scintillators were selected for the reference light power meter measurements, as detailed in Table S4. The reference light was scattered in the same geometry as the Yb$^{3+}$:CsPbCl$_3$ scintillator. To match the commercial CaF$_2$(Eu) and CsI(TI) scintillators, the reference light measurement was performed with a polished glass cube with the same dimensions and geometry as the commercial scintillators inside an integrating sphere (Figure S4). For the Yb$^{3+}$:CsPbCl$_3$ scintillators, the reference light was scattered using CsPbCl$_3$ powder in the same capillary configuration and with the same geometry as the Yb$^{3+}$:CsPbCl$_3$ scintillator. The number of emitted photons from each scintillator was calculated with calibration using reference light power measurements and PMT detector counts.

#### 4.4.4. Quantifying Photon Output of Scintillators
The photon output of the xenon lamp light source with a monochromator was used in conjunction with a power meter and PMT detector to determine the photon output of the commercial CaF$_2$(Eu) and CsI(TI) scintillators and the Yb$^{3+}$:CsPbCl$_3$ scintillators. Wavelengths matching the emission of commercial and Yb$^{3+}$:CsPbCl$_3$ scintillators were selected for the reference light power meter measurements, as detailed in Table S4. The reference light was scattered in the same geometry as the scintillators. To match the commercial CaF$_2$(Eu) and CsI(TI) scintillators, the reference light measurement was performed with a polished glass cube with the same dimensions and geometry as the commercial scintillators inside an integrating sphere (Figure S4). For the Yb$^{3+}$:CsPbCl$_3$ scintillators, the reference light was scattered using CsPbCl$_3$ powder in the same capillary configuration and with the same geometry as the Yb$^{3+}$:CsPbCl$_3$ scintillator. The number of emitted photons from each scintillator was calculated with calibration using reference light power measurements and PMT detector counts.

#### 4.4.5. Quantifying Energy Deposited Using Commercial Scintillators
Complete X-ray absorption by each of our sample was confirmed using the methodology illustrated in Figure S5a,b. The sample being tested for total X-ray absorption was positioned right outside the integrating sphere port in the path of the X-ray beam. A commercial scintillator [CsI(Na)] was positioned inside the integrating sphere to detect any X-rays transmitted through the sample. Complete X-ray absorption by the tested scintillator was confirmed by the absence of CsI(Na) scintillated photons. The cubic CaF$_2$(Eu) and CsI(TI) scintillators completely absorbed the X-ray beam, as did 12 Yb$^{3+}$:CsPbCl$_3$ powder filled capillaries, stacked into two rows (Figure S5c-e).

Finally, the energy deposited by the X-ray source was calculated using the CaF$_2$(Eu) and CsI(TI) commercial scintillators. The values were corrected using the non-proportionality of CaF$_2$(Eu) and CsI(TI), 85 and 115%, respectively. The deposited energy was determined to be $2.08 \times 10^7 \text{ MeV} \pm 0.28 \times 10^7 \text{ MeV}$ with CsI(TI) and $2.19 \times 10^7 \pm 0.24 \times 10^7 \text{ MeV}$ with CsI(TI).

#### 4.4.6. Light Yield of Yb$^{3+}$:CsPbCl$_3$
The light yield of the 5% Yb$^{3+}$:CsPbCl$_3$ scintillator was calculated using an energy deposited value of $2.4 \times 10^7 \text{ MeV}$, which is the highest value in the range of the measurements described in Materials and Methods Section 4.4.5. We chose the highest value for the deposited energy to be conservative and obtain lower limit values of the light yield. Resolution of the radioluminescence emission spectra of Yb$^{3+}$:CsPbCl$_3$ was not affected by equipment parameters within the linear range of the detector. The light yield of the 5% Yb$^{3+}$:CsPbCl$_3$ was determined to be 102,000 photons/MeV with a standard deviation of 877.

### 4.5. Radiographic Imaging
Radiographic images were captured using a Basler ace acA1300-60gm-NIR GigE camera with a 4.5 mm C Series vis−NIR fixed focal length lens. The images were captured on the surface of the 25 mm 5% Yb$^{3+}$:CsPbCl$_3$ pressed powder pellet using the benchtop X-ray source at 40 kV and 300 μA and a 5.5 s exposure time.

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**ASSOCIATED CONTENT**

* Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c01712.

XRD results, EDXS images, elemental composition, and details of experimental methods (PDF)

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