Bulk Luminescent Solar Concentrators Based on Organic-Inorganic $\text{CH}_3\text{NH}_3\text{PbBr}_3$ Perovskite Fluorophores

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Abstract

In this paper, we report characterization and performance results of lead bromide perovskite luminescent solar concentrator. $\text{CH}_3\text{NH}_3\text{PbBr}_3$ fluorophores are synthesized by sonication method and examined by their X-ray diffraction pattern and scanning electron microscopy. Synthesized perovskite shows excitonic absorption at 524nm and PL emission peak located at 532nm with a Stokes shift around 8nm. Micron-sized fluorophores are dissolved in prepared solutions and uniformly embedded in PMMA host with 0.006% to 0.120%wt concentration. Then, Fabricated devices are cut into 50×30×5mm cuboid shapes and placed in a mirror surrounded configuration with an attached photovoltaic cell. Fabricated device is put under standard AM1.5 illumination and the output spectrum from the concentrator is acquired. Re-absorption in the samples is also measured by variable optical path method, showing red-shifts up to 13nm in the output spectrum. Spatially resolved photoluminescence maps and optical efficiencies are also presented for each sample. Plus, a Monte-Carlo ray tracing algorithm is developed to assist better understanding the experimental results. Stability of fabricated samples are evaluated under high intensity UV

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illumination, reporting efficiency reduction around 15% after 24 hours. Finally, Comparing current-voltage characterization of the attached photovoltaic cell reveals optimized efficiency enhancement in the 0.04%wt sample above 65%.

Keywords: Luminescent solar concentrators, Solar cells, Perovskites, Photovoltaic conversion efficiency, Re-absorption, Monte-Carlo simulation

1. Introduction

Due to the global issue of growing demand for energy and its environmental concerns, renewable energies such as solar energy are in the focal point of increasing attention [1, 2, 3]. Luminescent Solar Concentrators (LSC) as a solution not only address the financial concerns through employing cheaper or smaller sheets of Photovoltaic (PV) modules, but also offer to enhance the Power Conversion Efficiency (PCE) by increased diffused light collection and also possible solar grid integration in buildings and vehicles. LSC is a transparent polymer slab with mirrored bottom and side faces that acts as an optical waveguide containing dispersed luminescent materials. Absorbed sunlight in the LSC is down-converted to longer wavelenghtes through the photoluminescent emission of the incorporated dyes. Since the host polymer matrix has higher refractive index than the environment, emitted photons by the fluorophores are guided according to the total internal reflection in the LSC. A PV cell is attached to one edge of the LSC for photon collection and current generation [4]. Advantages of LSCs such as their lighter weight, simplicity of fabrication, functionality under both diffuse and direct lighting condition and also eliminating the need for sun-tracking and focusing systems further reveal their significant role in the PV research [5]. Recent studies also suggest mounting LSCs on a vertical semi-transparent solar windows for building-integrated PV applications [6]. Features of an appropriate fluorophore for LSC applications include high Quantum Yield (QY), broad absorption range, large stokes shift and strong Photo-Luminescence (PL) emission in the vicinity of the highest spectral response of the attached solar cell [7]. Because of their high QY, laser dyes such as Rhodamines, Coumarins, and

4-dicyanomethylene-2-methyl-6-(p(dimethylamino)styryl)-4H-pyran (DCM) are
 common and inexpensive luminescent materials for LSCs [8]. However, most of
 these materials suffer from spectral overlapping between absorption and emis-
 sion spectra. For instance, doping PMMA with organic DCJTB dye only leads
 to 1.9% increase in PCE [9]. Tandem-waveguide organic solar concentrators
 is also an alternative method to enhance the efficiency of LSCs [10]. Employ-
 ing organic dye mixtures in the polymer waveguide is another approach toward
 higher PCEs [11]. Efficiency enhancements above 7% is reported by embed-
 ding Lumogen and fluorescence Yellow CRS040 as organic dyes in the PMMA
 matrix [12]. Semiconductor Quantum Dots (QDs) exhibit more stability and
 also offer tunable emission wavelength by varying the diameter. This controlled
 luminescence wavelength is helpful for minimizing the unfavored overlap of ab-
 sorption and emission spectra in LSCs [8, 13]. Diverse semiconductor QDs like
 core-shells of CdSe/ZnS, CdSe/CdS, PbS/CdS and core-multishells of CdSe are
 incorporated in polymer slabs for LSCs applications [8, 13, 14, 15, 16]. Em-
 ploying these QDs has led to giant enhancement in the LSCs optical efficiency.
 For example, CdSe/CdS QDs with a QY around 86% and geometrical factor
 of 3 oer 48% boost in the optical eciency of the LSC. Also, PbS/CdS quan-
 tum dot based LSCs have an optical efficiency of 1% with geometrical factor of
 45 [14, 16]. Despite being recently introduced as PV materials, other features
 of perovskite semiconductors such as high refractive index, broad absorption
 spectrum, high QY and large stokes shift suggest their possible application as
 a luminescent fluorophore in LSCs [17]. The structure of a perovskite is in the
 form of ABX_3 : A is an organic or inorganic cation ($CH_3NH_3^+$, $CH(NH_2)^{2+}$,
 Cs), B a divalent cation (Pb, Sn) and X stands for halides(Cl, Br, I). Changing
 the halide component in perovskite semiconductors tunes their direct band gap.
 Large absorption coefficients and high carrier mobilities are also confirmed in
 these materials [18]. In 2015, our group has introduced the first application of
 $CH_3NH_3PbBr_3$ perovskites as luminescent dyes for PCE enhancement. There, a
 thin perovskite film (100 microns) was deposited on Si PV solar cell and shown
 55 that increasing the molar ratio of organic to inorganic part in this material

enhances the output I-V performances of the employed PV cell. Furthermore, optimized perovskite concentration was found to be around 7.0 wt%, leading to a 45% efficiency improvement compared to the bare PV cell [19]. Continued studies by Nikolaidou et al. [17] on the ratio of PbAc2 precursor in $\text{CH}_3\text{NH}_3\text{PbI}_3$ synthesis has led to a maximum film coverage in the thin film architecture. It has been demonstrated that the 50% PbAc2 sample appears to have the most homogenous PL emission with the highest intensity and the sample with 90% acetate content exhibits a maximum optical efficiency of 29%. Fabrication of perovskite-based bulk LSCs with $\text{CsPb}(\text{Br}_x\text{I}_{1-x})_3$ mixed halide quantum dots was first reported by Zhao et al. [20]. They also achieve enlarged Stokes shift of QDs by tuning the chemical composition ratio between Br and I. Prepared perovskite QDs with 20% Br concentration exhibit the highest QY over 60% and good photostability. The external optical efficiency of 2% is also reported for the $\text{CsPb}(\text{Br}_{0.2}\text{I}_{0.8})_3$ mixed halide QDs incorporated in LSC.

Compared to our previous study on thin luminescent perovskite films, in which CH_3NH_2 and HBr are mixed at 0°C and then PbBr_2 is added to the solution to make bromide perovskite [19], here we synthesized the perovskite fluorophores through the sonication method. In what follows, rather than the thin film geometries, we focus on realization of the bulk $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite LSCs. First, methodology for the synthesis of lead halide perovskite micro particles is presented. Then, it is followed by a recipe for uniformly embedding synthesized fluorophores in PMMA matrix and fabricating LSCs. An algorithm based on Monte-Carlo ray tracing method is also included to assist better comprehension of the results. Structural and optical properties of the manufactured LSCs are presented and discussed. Finally, results of characterization under standard sun illumination are provided.

Figure 1: Timeline for $\text{CH}_3\text{NH}_3\text{PbBr}_3$ sonication synthesis and emitted PL under UV-lamp

2. Materials and Methods

2.1. Chemicals

Lead Bromide (PbBr_2 , 98%), isopropanol (99.5%), Methyl Methacrylate (MMA, 99%), Poly Methyl Methacrylate (PMMA, $M_w = 996000$) and 2,2-Azobis-2methylpropionitrile (AIBN, 98%) were purchased from Sigma-Aldrich and used as received. MMA and AIBN are used as monomer and radical initiator, respectively. Methyl Ammonium Bromide (MABr) was prepared according to published methods in literature [21, 22].

2.2. Synthesis

The synthesis process of perovskites involves sonication of two $\text{CH}_3\text{NH}_3\text{Br}$ and PbBr_2 precursors which are dissolved in isopropanol [23]. First, 8mL of a 0.25M $\text{CH}_3\text{NH}_3\text{Br}$ solution was transferred into a glass test tube and sonicated for 30s with ultrasonic transducer (Qsonica-Q700 20kHz) operating at 60% of its maximum amplitude. Then, continuing the sonication for 20 minutes, 6mL of 0.25M PbBr_3 solution was added drop-by-drop. Synthesis temperature was monitored and stabilized around 39-40°C by immersing the sonication cell in a water bath with an attached thermocouple. A Change in the color from white to orange was observed right after mixing the chemical precursors. As shown in Fig. 1, indicative of the chemical reaction, emitted PL from the solution under UV illumination is increased with sonication time.

Figure 2: LSC casting mold (a), Fabricated LSCs with different concentrations from 0 (pure PMMA) to 0.12%wt under visible (up) and UV (down) illuminations (b) and mirror configuration for IV characterization (c).

2.3. Device Fabrication

First, pure MMA solution is heated to 60°C and then the PMMA is added with 9:1 (MMA:PMMA) weight ratio. Once the PMMA is dissolved, the solution is quenched and desired amount of the synthesized perovskite along with 0.8wt% of polymerization initiator (AIBN) is added [24]. In this study, we have fabricated six solutions with perovskite concentrations ranging from 0.006 to 0.12%wt of MMA+PMMA solution. A pure PMMA solution is also fabricated as the reference LSC. Subsequently, the mixture is poured in to a casting mold where the polymerization is initiated. The casting mold (depicted in Fig. 2-a) was made by clamping two glass plates sealed with a Poly Vinyl Chloride (PVC) gasket to preserve the inert atmosphere. Gaskets with thickness of 5mm are used which impose this value to the thickness of fabricated LSCs. Afterward, mold is placed in a water bath at 60°C for 18 hours and then in the oven at 80°C for 2 hours. Finally, samples are cut to $50 \times 30 \times 5\text{mm}$ using a laser cutter (Universal Laser Systems) and the cuboid faces are polished (Fig. 2-b).

2.4. Characterization

Fabricated LSCs are illuminated under AM1.5 global solar simulator ($100\text{mW}/\text{cm}^2$). A PV cell with previously measured characteristics is attached to one edge of the LSC. Other faces including the bottom surface are coupled to optical mirrors,

Figure 3: Employed AM1.5 standard solar spectrum and its corresponding CDF (a), PL emission spectrum of $CH_3NH_3PbBr_3$ and calculated CDF (b).

see Fig. 2-c. Output spectrum from the edge of LSCs is obtained by fiber-coupled Ocean Optics USB4000 spectrometer. Optical properties of synthesized materials and LSC are acquired by Shimadzu UV-2450 spectrophotometer and Jasco FP-6200 spectrofluorometer. X-Ray Diffraction (XRD) spectrum is attained by Siemens XRD-D5000 diffractometer. For reporting the morphology of the materials, Tescan MIRA3 Scanning Electron Microscope (SEM) is employed. FOIS-1 integrating sphere spectroscopy device is used for acquiring the optical efficiency and output power from the LSC edges.

2.5. Simulation

We have developed a Monte-Carlo ray tracing algorithm for simulating the response of LSCs. Monte-Carlo method is a numerical approach in Physics and Mathematics based on random sampling from statistical possibilities. It is applicable to any problem for which a clear domain of possibilities is defined. According to the law of large numbers, adequate number of repeated sampling leads to results close to the reality [25, 26]. First, Cumulative Distribution

Function (CDF) of the incident AM1.5 spectrum is calculated via [27]:

$$CDF(\lambda) = \frac{\int_{\lambda_{min}}^{\lambda} P(\lambda') d\lambda'}{\int_{\lambda_{min}}^{\lambda_{max}} P(\lambda') d\lambda'} \quad (1)$$

Where, P represents the wavelength dependent power of the incident light (see Fig. 3-a). Then, a random number ($\xi \in [0,1]$) is generated and set equal to the above calculated CDF to extract the wavelength (λ) above. The reflection coefficient for a normal incident on the LSC (n=1.5) is calculated as 4% and if ξ generates a value larger than this value the photon enters the LSC. Absorption length (l_{abs}) for the photon is determined by absorbance spectrum ($\alpha(\lambda)$) of the fluorophore through [28]:

$$l_{abs} = -\frac{\log(1 - \xi)}{\alpha(\lambda)/t} \quad (2)$$

Thickness of the sample for obtained absorbance spectrum is denoted as t . Mirrors are defined in the equations and the photon is moved in the LSC. When l_{abs} is reached, the photon is absorbed by a dye. Comparison of ξ with the quantum yield of dye again determines whether the photon is quenched or another photon is re-emitted. In the case of re-emission, wavelength of the re-emitted photon is defined by another CDF which is generated from the photoluminescence spectrum of the fluorophore (see Fig. 3-b). l_{abs} for the re-emitted photon is recalculated and the loop is restarted. This process is repeated for desired amount of the sampling [29].

3. Result & Discussion

3.1. Structural Properties

To investigate the formation of $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite, synthesized fluorophore was analyzed using XRD to determine its crystal structure. First of all, a color change from white to orange was observed right after mixing the two precursors, indicating the formation of perovskite fluorophore. In Fig. 4-a, x-ray diffraction pattern for $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite is depicted. This plot shows peaks at $2\theta = 15.1, 21.3, 30.2, 33.9, 37.3, 43.3$ and 46.07 that are assigned to

Figure 4: X-ray diffraction pattern (a) and scanning electron microscope image of the synthesized $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite (b).

the diffraction planes of (100), (121), (200), (240), (141), (220) and (300), respectively. These peaks are established characteristic of the cubic $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite structure [30]. These interpretations are also confirmed by SEM image of the synthesized fluorophore that demonstrates formation of the perovskite cuboids with multi-micron diameters, see Fig. 4-b.

3.2. Optical properties

The absorption spectrum of $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite suspension in isopropanol solvent is reported in Fig. 5. The emission spectra of bromide perovskite is also presented in the same figure. According to our studies, there is not a considerable difference between the PL emission of $\text{CH}_3\text{NH}_3\text{PbBr}_3$ dyes in isopropanol compared to its spectrum after polymerization in PMMA host. Located excitonic absorption at 524nm and PL emission peak at 532 nm indicates a Stokes shift around 8nm for this materials. Full Width at Half Maximum (FWHM) for the emission peak is measured around 25nm. Loss pathways for a photon in LSC devices include reflection from the top surface (4% for normal illumination), not being absorbed by the fluorophore, absorbed by fluorophores but not emitted (non-unity QY), re-emitted photon loss due to the escape cone

Figure 5: Absorption spectrum of $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskite suspension in isopropanol (black) and its PL emission under 350nm excitation (blue).

and re-absorption of the re-emitted photons. Seeing that the absorption edge and PL emission peak are placed near to each other, re-absorption of the emitted photons plays a crucial role in these materials. Since we already have shown that synthesized $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskites have typical QYs around 75% [19], we address the re-absorption as the major loss pathway. Self-absorption is the re-absorption of the light emitted by the luminescent material and subsequently re-emission at lower energies, which leads to a red-shift in emission wavelength. This re-absorption is measured by a quality Factor (QF) parameter that is defined by [31]:

$$QF_{LSC} = \frac{\alpha_{excitation}}{\alpha_{PL}} \quad (3)$$

Where, $\alpha_{excitation}$ and α_{PL} represent absorption coefficient at the incident and PL emission wavelength, respectively. Measured QF in $\text{CH}_3\text{NH}_3\text{PbBr}_3$ perovskites is about 1.2, consistent with the observed Stokes shift in these materials. In order to evaluate re-absorption in the fabricated LSCs, we benefit from variable optical path method ([32]). In this technique which is illustrated in Fig. 6a, fabricated LSCs are illuminated by a diode laser ($\lambda=437\text{nm}$) through pin holes having the same diameter of $1\mu\text{m}$ but positioned with different distances to the collection face. Optical path is varied from 5 to 50mm, limited

Figure 6: Experimental setup for measuring re-absorption (a), Green PL emission under $\lambda=437\text{nm}$ excitation (b) PL emission from the edge of samples for diverse optical paths (c) and induced PL red-shift at 5cm illumination.

(a)

(b)

Figure 7: Spatial resolved photoluminescence maps of LSCs under UV light(a) histogram of emission domains for different concentrations (b)

by the length of the samples. PL emission from the LSC edge at the position of attached PV cell (Fig. 6-b) is collected by a fiber-coupled spectrometer for diverse optical paths. Fig. 6-c shows output PL intensity measured at the position of PV cell as a function of optical path. Obviously, in the absence of the re-absorption, PL spectra would not change by altering the optical path. Appeared reduction in the output intensity is a result of spectral distortion due to the photon re-absorption. It should be noted that re-emitted photons with angles smaller than the critical angle are also contributing to the reabsorption calculations by escaping the device from the top surface. According to this figure, higher concentrations tend to show an abrupt loss with increasing the optical path. Besides, the output PL spectrum reveal maximum red-shift values up to 13nm (Fig. 6-d) associated with a slight narrowing trend around 2-3nm for the FWHM at longer optical paths.

Quantum yield for the Perovskite fluorophores was calculated in our previous study [19]. However, in order further evaluate the performance of this dye in a concentrator, we have also studied the optical efficiency of LSC containing Perovskite dyes. To that end, we use integrating sphere spectroscopy (Ocean Optics) to obtain the output power from the LSC edges. In this method, the upper surface of the LSC is completely covered by AM1.5 standard illumination ($OP_{IN}=1500$ mW) and the output spectrum from the LSC edges is scanned with 1×0.5 cm² steps [33]. The total emitted optical power from the LSCs (OP_{OUT}) are calculated by integrating the obtained spectrum from the edges. Result for this measurement are depicted in Table. 1. Optical efficiency ($\eta_{Optical}$) stands for the ratio of output power(OP_{OUT}) from the edges to the input power (OP_{IN}). According to the provided data, 0.04%wt sample has the highest optical efficiency, 50% higher than that of pure PMMA sample. These reported values for the optical efficiency and output power are comparable to the previous works [33, 34]. Spatial resolved PL results are also presented to examine fluorophore distribution in the LSC samples, see Fig. 7-a. Real images shown in this figure are magnified PL emission from 1cm² of the samples under UV illumination. Then, an algorithm is employed to convert and digitalize these im-

Table 1: Optical efficiency and output power of the LSC samples obtained by integrated sphere power calculations.

Sample	$\eta_{Optical}(\%)$	$OP_{OUT}(mW)$
pure PMMA	0.79	11.9
0.006%wt	0.98	14.73
0.012%wt	1.35	20.29
0.026%wt	1.53	22.98
0.040%wt	1.57	23.52
0.080%wt	1.21	18.18
0.120%wt	1.12	16.73

ages. Final images are constructed by reducing the image resolution and measuring the output intensity from each domain. Obviously, higher fluorophore concentration generates larger amount of photon emission and makes the final images brighter. Brightness homogeneity of these maps is an indication of fluorophore dispersion uniformity in the polymer matrix. In the histogram of intensity (Fig. 7-b), 0.026%wt sample emits comparable number of photons from each pixel and thus has a narrower curve than that of other samples. Although 0.12%wt sample with the highest concentration has the strongest luminescence intensity, measured re-absorption for this sample shows the highest loss and thus reduces its overall performance.

3.3. Characterization

Measured and simulated output spectrum from the 0.04%wt LSC output edge are plotted in Fig. 8-a. In spite of lowered overall transferred power, UV portion of the spectrum is absorbed by perovskite fluorophores and re-emitted as absorbable green light. In order to account for collected photons with wavelengths lower than the PL emission, we have also introduced scattering in our simulations. Without scattering, the output spectrum would consist of a single PL emission peak. After this calibration, good agreement between the Monte Carlo ray tracing and experiment is observed. This coherency grants us to ben-

Figure 8: Measured and averaged simulated output spectrum from 0.04%wt LSCs compared to the standard AM1.5 illumination(a), Collected incident photons and output power for diverse geometrical factors (b)

Figure 9: IV curve (a) and output power (b) of employed Silicon PV cell attached to LSC samples

Table 2: Comparison of the PCE for different fluorophore concentrations

Sample	V_{OC} (V)	I_{SC} (mA)	FF(%)	η (%)	$\Delta\eta$ (%)
pure PMMA	6.3	3.40	37.8	3.24	0
0.006%wt	6.3	3.56	42.1	3.78	16.7
0.012%wt	6.3	3.46	43.4	3.78	16.7
0.026%wt	6.3	4.10	40.9	4.23	30.7
0.040%wt	6.3	5.40	40.0	5.44	68.0
0.080%wt	6.3	4.10	40.9	4.23	30.7
0.120%wt	6.3	3.67	42.5	3.93	21.3

25 efrit from the simulations to theoretically optimized the device. Since the input
 26 and output areas of LSC are defined by length $\times$ width and thickness $\times$ width, the
 27 only effective *geometrical factor* is defined as the ratio of LSC length to its thick-
 28 ness. According to our simulations depicted in Fig8-b, increasing geometrical
 29 factor enhances the output energy. However, due to the introduced scattering
 30 and re-absorption in the system, increasing the geometrical ratio leads to a plum-
 31 meted number of collected photons. But, increased capture cross-section raises
 32 the intensity with compared to that of LSCs with smaller geometrical factors.
 33 It is shown that by raising geometrical factors from 1 to 50, the output power
 34 increases approximately from 13% to 15%. For geometrical factors higher than
 35 50, the increase slope is reduced. Thats why geometries having large geomet-
 36 rical factors, like cylindrical shapes, are gathering more attention [35]. Next,
 37 IV curves for the employed Silicon PV cell attached to the LSC samples with
 38 different fluorophore concentrations are obtained, see Fig9. Calculated short-
 39 circuit current (I_{SC}), open-circuit voltage (V_{OC}), filling factor (FF), PCE (η)
 40 and PCE increase compared to pure PMMA LSC ($\Delta\eta$) are depicted in Table2.
 41 The efficiency of LSC is obtained through comparing the PCE of the attached
 42 PV cell in Fig2-c under standard AM1.5 illumination [33]. In the case of lower
 43 concentrations (0.006%wt), UV spectrum is re-emitted with wavelengths of PL
 44 emission and due to the lower dye domains, the overall efficiency only shows 16%

Figure 10: Relative efficiency of LSCs versus time under 9W UV lamp.

increase regarding the pure PMMA LSC. The efficiency is further increased as dye concentration reaches 0.04%wt. Previously confirmed to have the highest optical efficiency, 0.04%wt sample provides PCE enhancements around 68%. Further increasing the fluorophore concentration brings about higher scattering as well as re-emission, re-absorption and photon escape that lead to lower efficiencies. Our results represent an optimized concentration around 0.04%wt for the maximum PCE enhancement. Expectedly, the open-circuit voltage which is related to the band structure of the PV cell is remained the same. Attached PV cell to the LSC configuration under direct AM1.5 sun light delivers PCEs around 9.2% with a FF of 24.5% and I_{SC} equal to 14.9mA. According to the Table 2 PV cell under normal AM1.5 has higher PCE than that of other data which are obtained when it is attached to the LSC configuration. However, advantages of perovskite LSCs such as lighter weight, simplicity of fabrication, diffuse light collection and possible integration onto the transparent building and vehicle windows surpass this weakness [33, 34].

Durability of the Perovskite materials is among the main concerns about their employment in LSC devices. For this reason, we perform stability measurements through high intensity UV illumination (9W) of the samples and measuring their

relative PL emission versus time, see Fig10. It is shown that samples with lower concentrations (0.012, 0.026 and 0.04%wt) lose about 15% of their efficiency after 12 hours. However, LSCs with higher concentrations (0.08 and 0.12%wt) record losses around 25%. Continued measurements up to 24 hours (that are not depicted in the figure), did not show considerable variations for the LSCs with low dye concentration. Recorded durability for the 0.04%wt sample is in the range of previously reported values [33].

4. Conclusion

In summery, we synthesized micron-sized $CH_3NH_3PbBr_3$ perovskite particles via sonication method. Structure and morphology of the synthesized perovskite were analysed by XRD patterns and SEM images. After verifying the formation of $CH_3NH_3PbBr_3$, its optical attributes such as absorbance and PL emission were presented. An excitonic absorption peak at 524 and PL emission peak at 532 nm was indicative of a Stokes shift around 8nm. Then, obtained fluorophores were mixed with proper amount of MMA and PMMA to obtain uniformly distributed solutions with weight ratios from 0.006 to 0.12%. In order to fabricate bulk and large scale LSCs, solutions were polymerized by initiators in casting molds with gasket thickness of 5mm and cut in $3 \times 5 \text{ cm}^2$ cubic shapes. Re-absorption, as one of the major loss pathways and main concerns in the field of LSCs was investigated through the variable optical path method. Results show reabsorption-induced red-shifts up to 13nm in the output spectrum of the LSC for longer optical paths. Homogeneous fluorophore distribution in the samples was verified by spatially resolved PL microscopy under UV illumination. According to the narrowed spatial PL peak, it is concluded that the 0.04%wt sample offers the highest dye distribution uniformity. Optical efficiency of the LSCs was also investigated through the integrated sphere spectroscopy. We report optical efficiencies from 0.79 to 1.57% for the fabricated LSCs and the optimized value for the 0.04%wt sample. Output spectrum from the LSC edge is shown to have a broad spectrum starting from the PL peak rather than a sharp

peak. Confirmed by our simulations, this suggests the presence of scattering sites inside the polymer matrix which were originated from voids and impurities. According to the results in the characterization section and studying different Perovskite dye concentrations in the PMMA matrix, we report an optimized PCE enhancement around 68% for the 0.04%wt LSC. Finally, regarding the measured stability as well as their facile and scalable fabrication, proposed LSCs show reliable performance to cover a broad range of applications in the solar energy industry.

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