Supporting Information

Stable Bright Perovskite Nanoparticle Thin Porous Film for Color Enhancement in Modern Liquid Crystal Displays

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1. EDS SEM analysis

We used Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) to observe material distribution in the porous of the film. **Figure S1** shows the cross-section of the polymerized –MMA porous film. These films were coated with gold to make them conductive for SEM. Strong Br, Pb, and Cs signals were detected in the cross-section of the film, which confirmed the good dispersion of perovskite nanoparticles in the film, thus proving the good infiltration of the material into the pores.

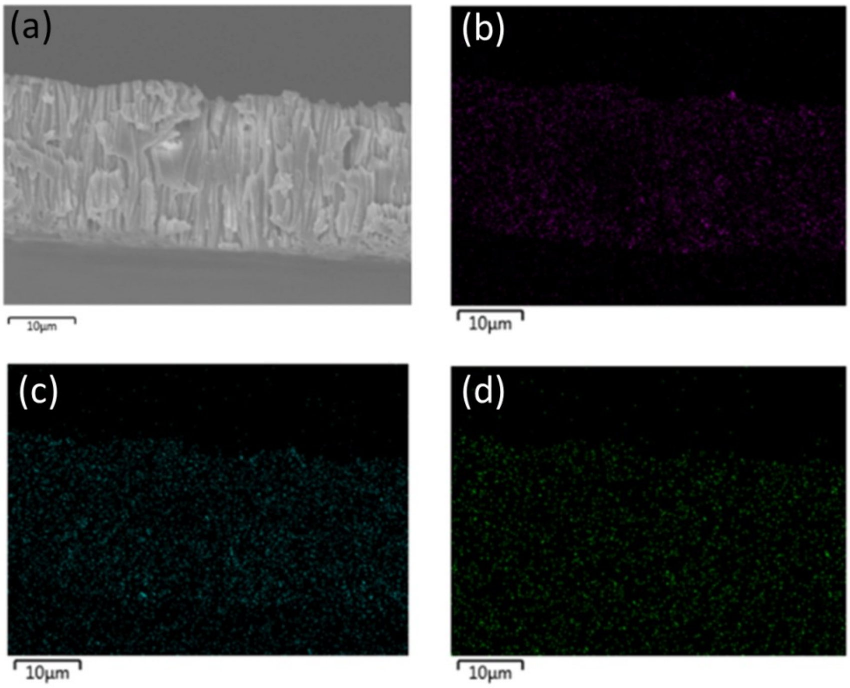

Figure S1: EDS SEM of the cross section of UV-polymerized $CsPbBr_3$-MMA in porous PET film. (a) SEM photo; (b) Br signal; (c) Pb signal; (d) Cs signal. (scale bar denotes $10\mu m$)

Figure S2 shows the top view of the same porous film. We observed some Comparing the location of pores and PET substrate, there are some signals of Br, Pb, and Cs are detected where there are no pores.

This illustrate that there is a layer of PNPs on the top of film. These PNPs are weakly protected, only by polymer matrix encapsulation from polymerized MMA matrix. Air and moisture can penetrate through this matrix.

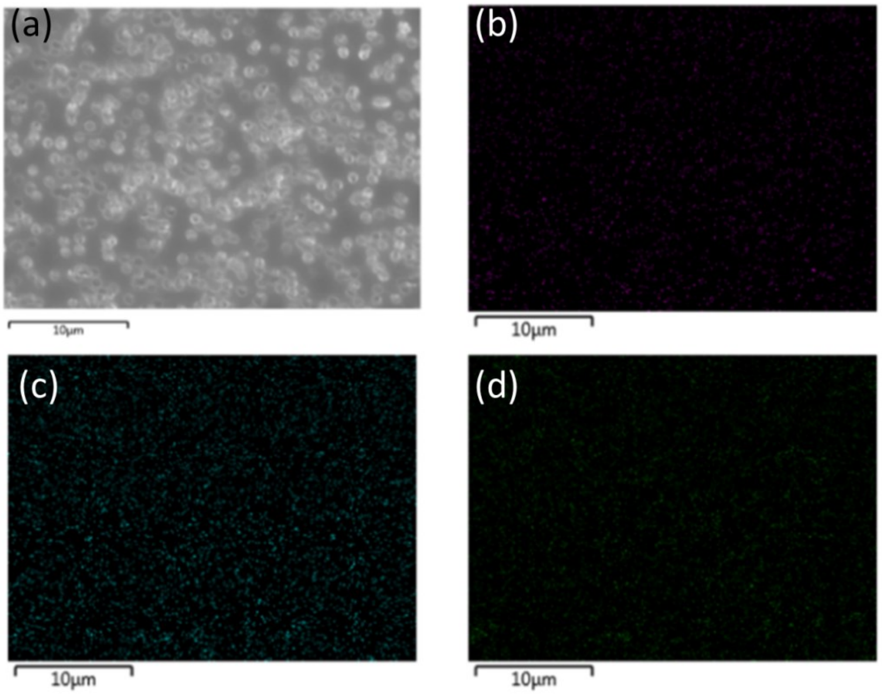

Figure S2: Top view EDS SEM UV of polymerized $CsPbBr_3$-MMA porous PET film. (a) SEM photo; (b) Cs signal; (c) Pb signal; (d) Br signal. (scale bar denotes 10μm)

2. Temperature dependent PL of PMMA PNP porous film.

Figure S3 shows the emission peak energy of PMMA PNP porous film with increasing temperature from 296K to 363K and its Equation fitting and **Figure S3 (b)** exhibits the fitting error. The data was fitted with method of the least squares fitting method.

The linear fitting results follows Equation (S1)

$$E_{peak}(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \qquad (S1)$$

In the equation, $E_g(0)$ is the bandgap energy at temperature 0K, α and β are characteristic constants for a certain material. Here, photoluminescence redshift 23meV with temperature varying from 296K to 363K. The fitting results gives parameter values: $E_g(0) = 2.405eV$, $\alpha = 2.43 \times 10^{-4}/K$ and $\beta = 202K$

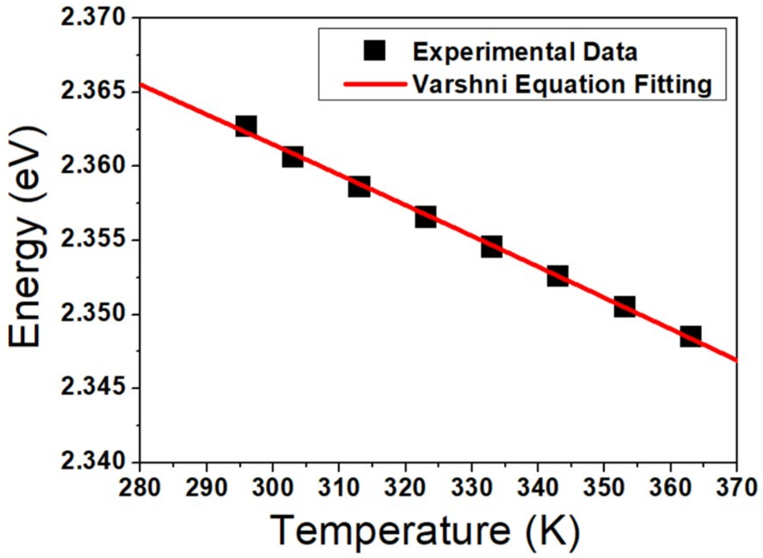

Figure S3: Varshni equation fitting of PMMA PNP porous film emission peak energy with increasing temperature.

Figure S4 shows the heating experimental results for the polymerized PNP-MMA film on a glass substrate. Samples were heated to and kept at 80°Cfor 16 hours and released to room temperature (23°C), naturally. About 90% of PL was lost after the heating treatment. Thus, the polymerized PNP-MMA film shows poor stability.

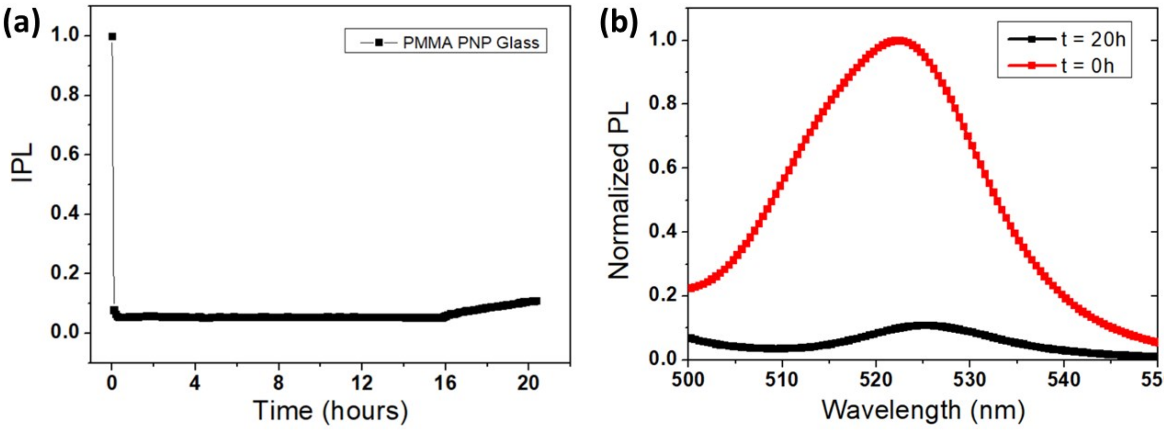

Figure S4: (a) Time evolution of normalized IPL of heating and cooling cycle for polymerized PNP-MMA on glass substrate. (b) Spectrum of samples in (a) at t=0h and t=20h for polymerized PNP-MMA on glass substrate.

3. Time-resolved Photoluminescence analysis

Details about Bi-exponential fitting result of photoluminescence decay are as follows. Fitting parameter for pure PNP bare PET film stored at different relative humidity (RH) (15%, 30%, 65%, 90%) for 15 hours can be found in **Table S1**:

Table S1: EDS SEM of the cross section of UV-polymerized $CsPbBr_3$-MMA in porous PET film

Sample Humidity	I_0	t_0 (ns)	A_1	τ_1 (ns)	A_2	τ_2 (ns)	$\tau_{average}$ (ns)
15%	0.01	17.0	0.60	1.9	0.40	6.5	5.1
30%	0.01	17.0	0.73	2.1	0.30	7.6	5.3
60%	0.01	16.9	0.64	2.0	0.36	7.7	5.9
90%	0.01	17.0	0.70	2.9	0.32	12.7	9.4

Table S2 exhibits the results for a pure PNP film stored 15 hours in 15% RH environment and measured after moving to 65% RH environment for certain time t.

Table S2: Top view EDS SEM UV of polymerized $CsPbBr_3$-MMA porous PET film.

Measure time	I_0	t_0 (ns)	A_1	τ_1 (ns)	A_2	τ_2 (ns)	$\tau_{average}$ (ns)
t = 0	0.01	17.0	0.62	1.9	0.38	6.8	5.3
t = 10 min	0.01	17.0	0.65	1.9	0.37	7.0	5.3
t = 20 min	0.01	17.0	0.65	2.0	0.36	7.1	5.4
t = 30 min	0.01	17.0	0.67	2.0	0.35	7.2	5.4
t = 90 min	0.01	17.1	0.65	2.3	0.36	8.5	6.5

Table S3 TRPL fitting error of average lifetime estimated by error propagation of each fitting parameter.

Table S3: TRPL fitting error of average lifetime.

Sample	RH 15%	RH 30%	RH 60%	RH 90%	RH 15% t = 0	RH 15% t = 10 min	RH 15% t = 20 min	RH 15% t = 30min	RH 15% t = 30min
$\tau_{average}$ (ns)	5.1	5.3	5.9	9.4	5.3	5.3	5.4	5.4	6.5
Error (ns)	0.5	0.2	0.4	0.5	0.4	0.4	0.3	0.4	0.1

Figure S5 shows the normalized instrument response function (IRF) (normalized intensity versus time).

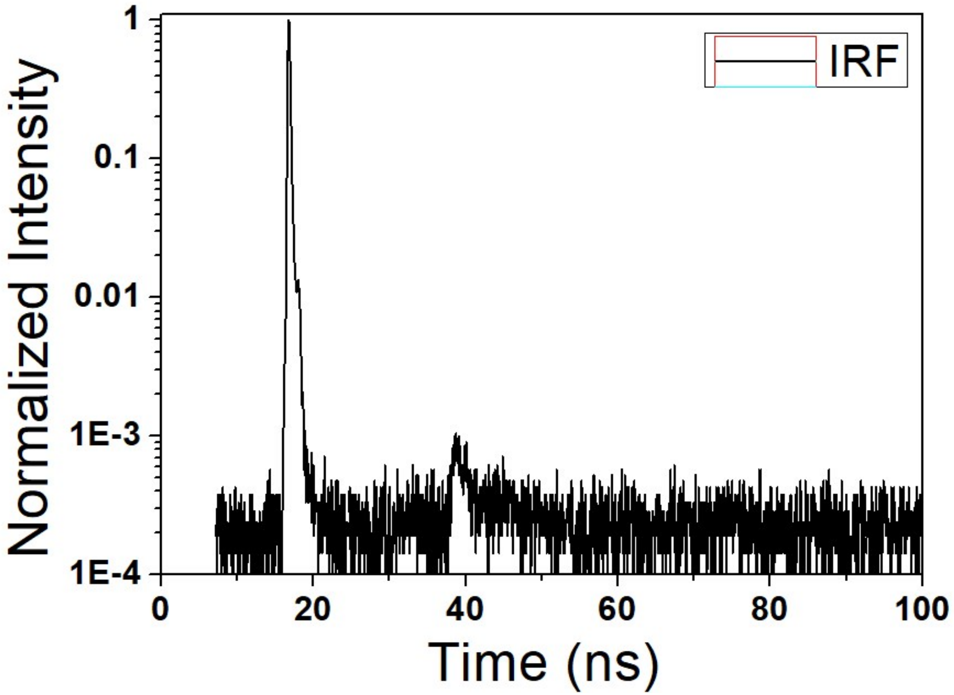

Figure S5: Top view EDS SEM UV of polymerized $CsPbBr_3$-MMA porous PET film.

4. In-situ photoluminescence performance of films at room temperature (296K) and a high relative humidity, RH 95%.

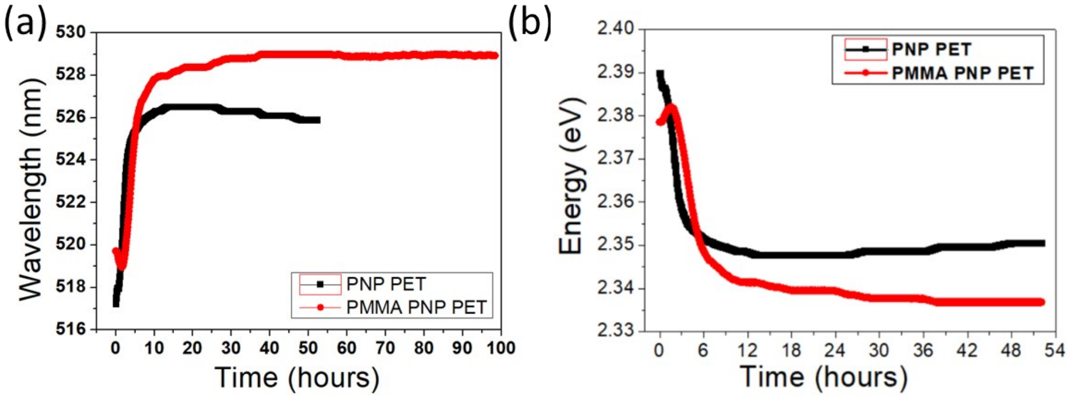

Figure S6: In-situ PL emission wavelength with time of various films at room temperature and high relative humidity of 95%. PNP PET stands for $CsPbBr_3$ nanoparticle bare PET film. PMMA PNP PET stands for polymerized MMA- $CsPbBr_3$ nanoparticle bare PET film.

Photoluminescence peak wavelength of PNP and polymerized PNP-MMA on bare PET (PMMA PET) film (black and red curve in **Figure S6**) both show redshift at high relative humidity (95% RH). The PNP PET film show redshift from 517nm to 526nm, with peak energy changing from 2.40eV to 2.36eV. Whereas, the PMMA PNP PET film show redshift from 520nm to 529nm, with peak energy changing from 2.38eV to 2.34eV. The redshift corresponds well to the enlargement of crystal size. The energy 2.34eV and 2.36eV are rather close to bulk $CsPbBr_3$ bandgap energy.

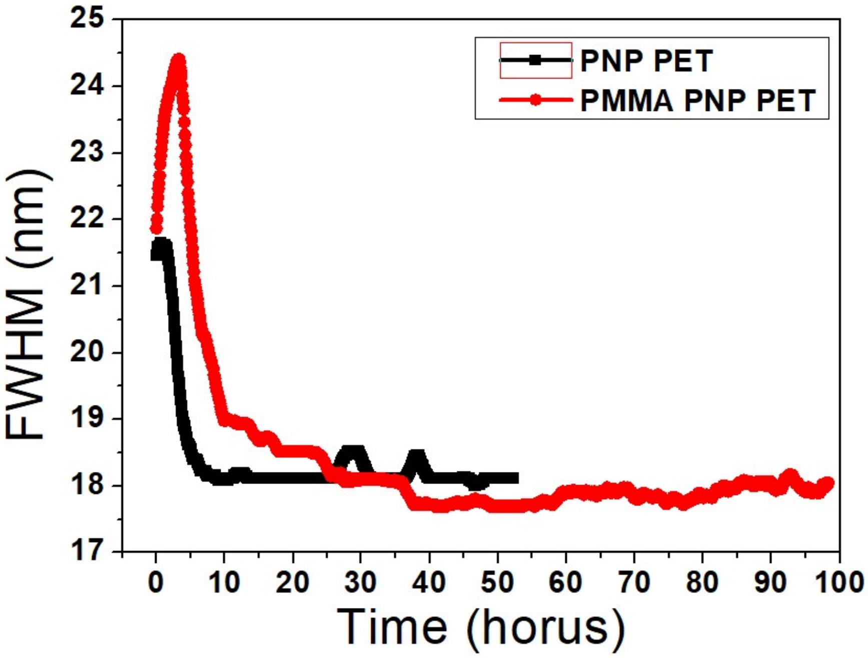

Figure S7: In-situ PL emission wavelength with time of various films at room temperature and high relative humidity of 95%.

Figure S7 shows the evolution of FWHM of PNP PL peak at 95% RH. The FWHM of films at high humidity decrease from 21.5 nm to about 18 nm. The decrease of FWHM with time manifests the refinement of PNPs at high humidity, leading to refined electronic band structure and better crystals of materials.

5. In-situ photoluminescence performance of films at room temperature (296K) and a moderate relative humidity, RH 65%.

Photoluminescence of pure PNP and polymerized PNP-MMA on bare PET (PMMA PET) film (red and blue curve in **Figure S8**) decreases over time in this environment, due to the synergistic influence of light illumination, moisture, and oxygen-induced degradation. For polymerized PNP-MMA in porous PET (Porous PMMA) film (black curve in **Figure S7**), PL initially decreases too. But this decreasing trend gradually stops, and the PL level maintains at about 70%, which is quite stable with very high repeatability. We believe that the initial decrease is a result of the residual layer of polymerized PNP-MMA on the top of the porous film. This layer, theoretically, has the same stability performance as the polymerized PET film, and therefore, after the initial degradation, the PNPs inside the porous film show good stability.

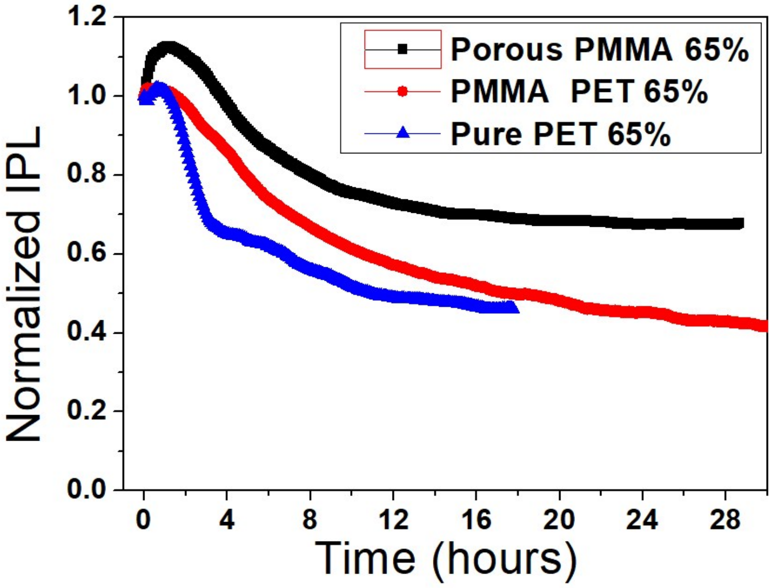

Figure S8: In-situ PL evolution with time of various films at room temperature and relative humidity 65%.

6. PLQY of various PNP films under different humidity condition

We measured PLQY evolution of PNP PET film, PMMA PNP PET film, and PMMA PNP porous film at different humidity conditions. Samples were prepared at the fixed humidity, and PMMA films were illuminated with UV, for 50 minutes, to polymerize the polymers. After preparation, starting from t = 1h, the film was illuminated with the same blue LED, similar to the in-situ PL experiments. (See **Table S4**)

Table S4: PLQY of various films at different humidity condition

Sample Number	Humidity [a] [RH %]	Sample Info	PLQY [%] (t=1 hour)	PLQY [%] (t=20 hour)	PLQY [%] (t=92 hour)
1	95	PNP PET [b]	25.26	26.2	16.48
2	95	PMMA PNP PET [c]	13.92	20.11	10
3	95	PMMA PNP porous [d]	22.68	22.12	18.05
4	15	PNP PET	22.55	8.06	2.88
5	15	PMMA PNP PET	5.04	3.72	1.08
6	15	PMMA PNP porous	8.04	7.04	2.97
7	65	PNP PET	22.63	14.52	7.65
8	65	PMMA PNP PET	11.71	10.96	6.27
9	65	PMMA PNP porous	21.28	16.12	12.23

[a] For each humidity, films were prepared and polymerized at this condition. Same as the MMA samples, PNP were also kept in this environment for 50 minutes but without UV exposure; [b] $CsPbBr_3$ NCs on bare PET film; [c] Polymerized MMA-$CsPbBr_3$ NCs on bare PET film; [d] Polymerized MMA-$CsPbBr_3$ NCs in porous film.

Compared to PMMA PNP PET samples, the PMMA PNP porous film still has high PLQY after the polymerization process at every humidity. At moderate to high humidity, the PMMA PNP porous film maintains high PLQY at the level, after exposing it in the alleged humidity and illumination condition for 92 hours above, higher than PNP PET films and PMMA PNP PET films.

7. LCD demo

The luminance of the blue BLU and LCD without the color filter is 180 nits. In CIE 1931 color space, the coordinate of blue backlight is (X,Y) = (0.1499, 0.0351). The luminance after adding the proposed PNP porous color enhancement film and a 500 nm long pass color filter is 236 nits. Color coordinate moves to (X,Y) = (0.1407,0.7434). The two coordinates are shown as the black points in Figure S9. For the brightness, the measured blue light intensity after the light guide plane is 0.28 mW that reduces to 0.03 mW after passing through the LCD and color filter. Thus, the efficiency of the CEF is around 10% .