

## Supplementary Information

### Phase Regulation via Dual Additives for Pure-blue Emitting Quasi-2D Perovskite Light Emitting Diodes

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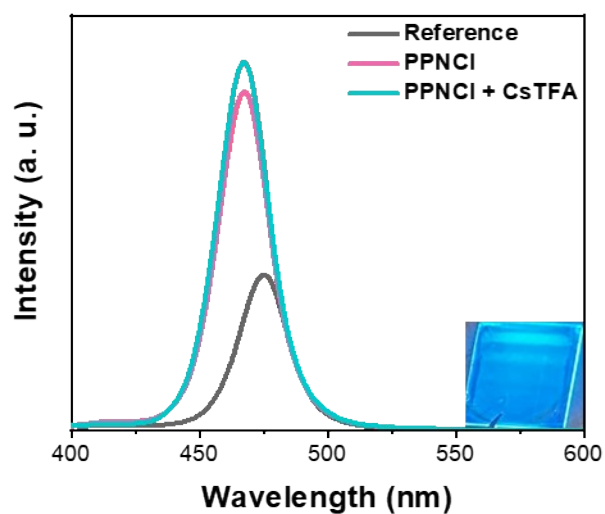
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TAS	$n = 2$ (ps)		$n = 3$ (ps)		$n = 4$ (ps)		$n \geq 5$ (ps)	
	$\tau_{\text{Rise}}$	$\tau_{\text{Decay}}$	$\tau_{\text{Rise}}$	$\tau_{\text{Decay}}$	$\tau_{\text{Rise}}$	$\tau_{\text{Decay}}$	$\tau_{\text{Rise}}$	$\tau_{\text{Decay}}$
Reference	0.18	0.53	0.16	0.36	0.16	1.36	0.32	149
PPNCI	0.12	0.24	0.10	0.33	0.14	0.33	0.18	53
PPNCI + CsTFA	0.16	0.13	0.13	0.25	0.11	0.33	0.13	44

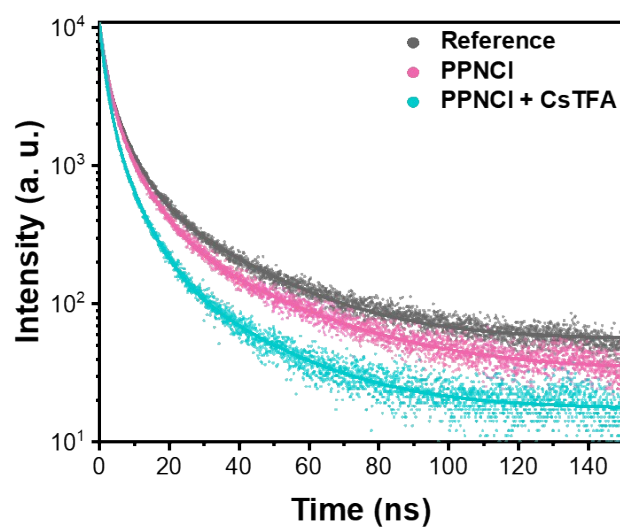
**Table S1.** Decay and formation constants for each condition at specific wavelengths corresponding to  $n = 2, 3, 4,$  and  $\geq 5$  Phases.



**Figure S1.** PL characteristics of perovskite films under reference, PPNCI, and PPNCI + CsTFA conditions; inset: perovskite film (PPNCI + CsTFA) under UV illumination.

Samples	Peak (nm)	FWHM (nm)	PLQY (%)
Reference	475	23	17
PPNCI	467	22	30
PPNCI + CsTFA	467	22	32

**Table S2.** PL characterization for each condition.



**Figure S2.** Time-resolved photoluminescence measurements for each condition.

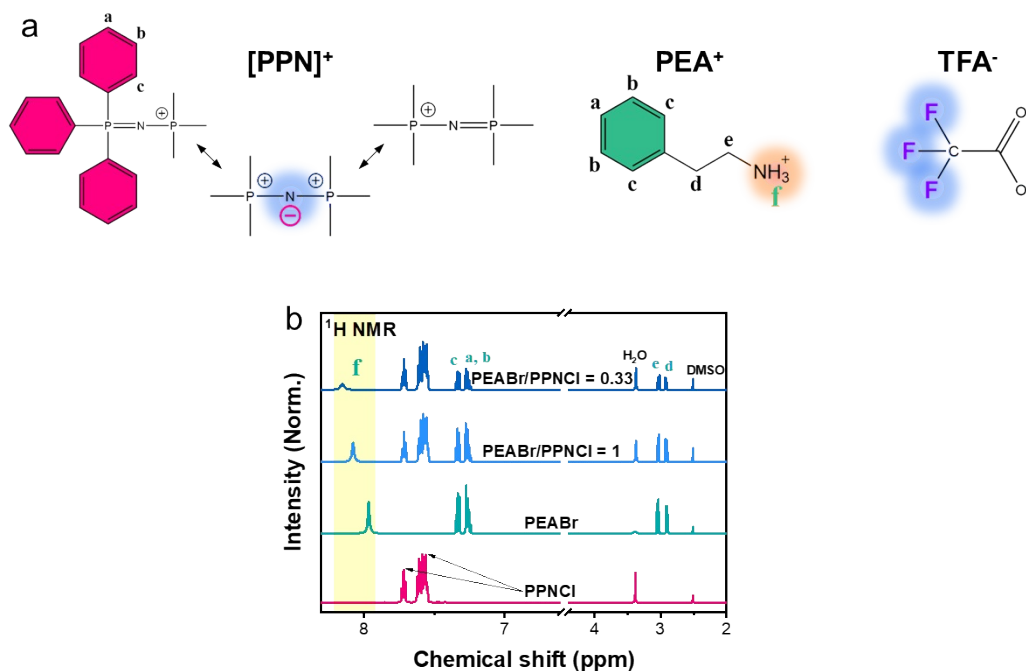
TRPL	PLQY (%)	$\tau_{\text{Decay}}$ (ns)		
		Avg.	Rad.	NR
Reference	17	12.2	72	15
PPNCI	30	11.5	38	16
PPNCI + CsTFA	32	7.7	24	11

$$y = A_1 \times \exp(-x/\tau_1) + A_2 \times \exp(-x/\tau_2) + A_3 \times \exp(-x/\tau_3)$$

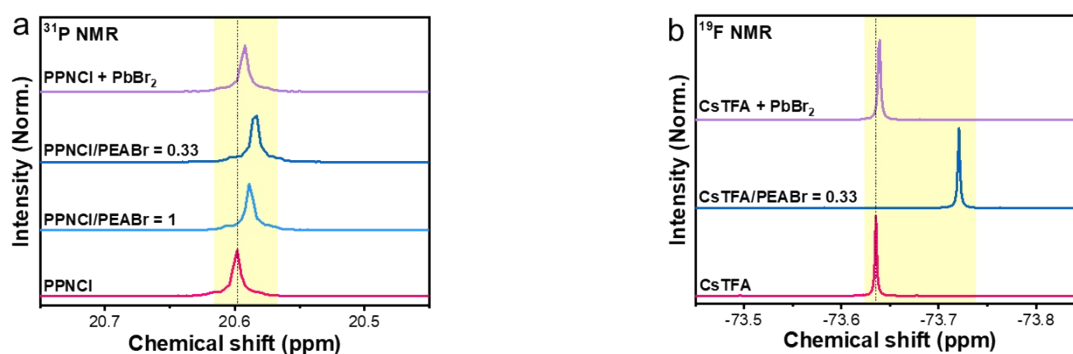
$$\tau_{avg} = \frac{\sum A_i \tau_i^2}{\sum A_i \tau_i} = \frac{1}{K_r + K_{nr}}$$

$$PLQY = \frac{K_r}{K_r + K_{nr}}, K_r = \frac{1}{\tau_{Rad.}}, K_{nr} = \frac{1}{\tau_{NR}}$$

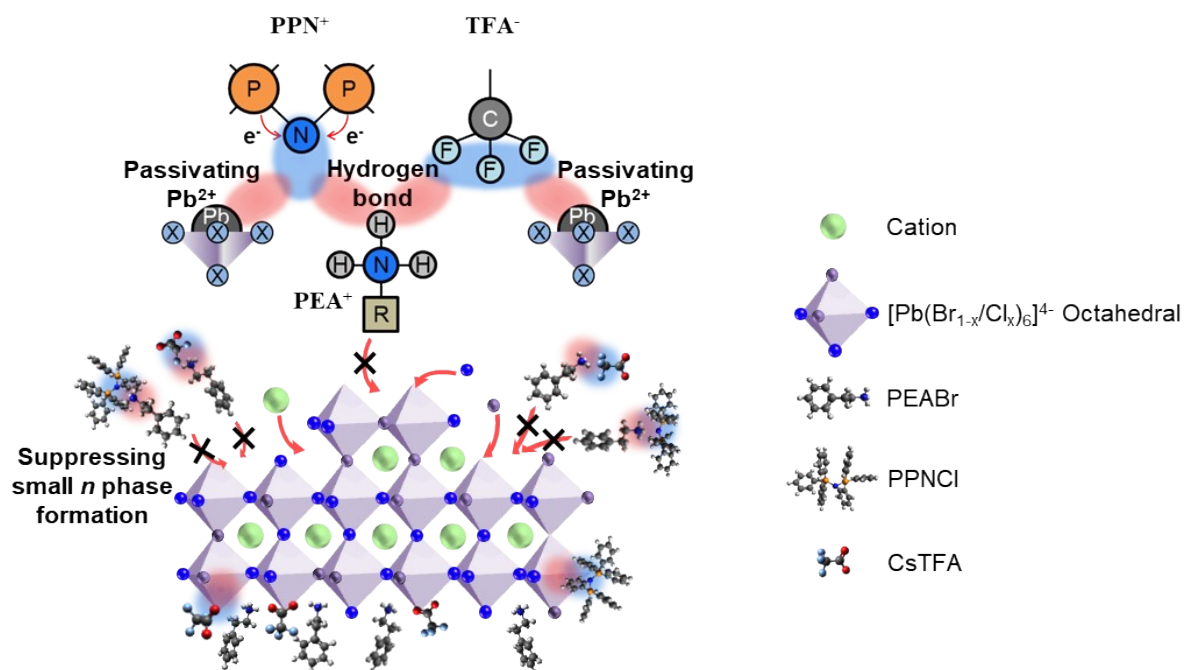
**Table S3.** PL decay times for each condition at specific wavelengths corresponding to the PL emission Peak. The reference condition corresponds to a wavelength of 475 nm, while PPNCI and PPNCI + CsTFA conditions correspond to 467 nm. ‘Avg.’ means average recombination, ‘Rad.’ means radiative recombination, and ‘NR’ means non-radiative recombination.



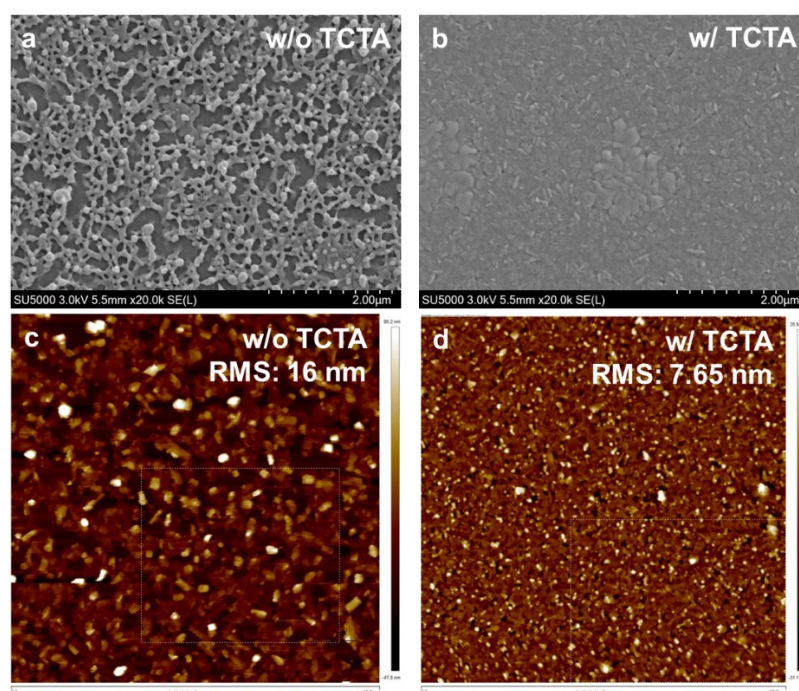
**Figure S3.** Hydrogen atoms in PEABr influenced by additives. (a) Schematic representation of the [PPN]<sup>+</sup>, PEA<sup>+</sup>, and TFA<sup>-</sup> structures. (b) <sup>1</sup>H NMR signals of PEABr at varying ratios of PPNCI to PEABr. The yellow ‘f’ region in (a) and (b) corresponds to the <sup>1</sup>H NMR signals of the ammonium group in PEABr.



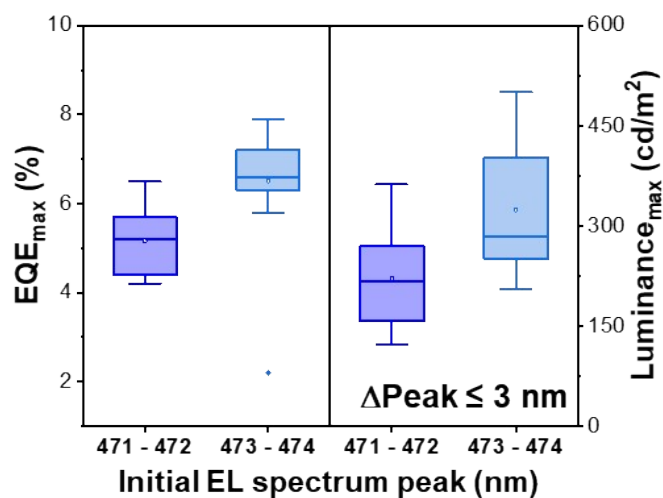
**Figure S4.** Interaction between spacers and additives. (a) <sup>31</sup>P NMR spectrum of PPNCI with and without PEABr. (b) <sup>19</sup>F NMR spectrum of CsTFA with and without PEABr.



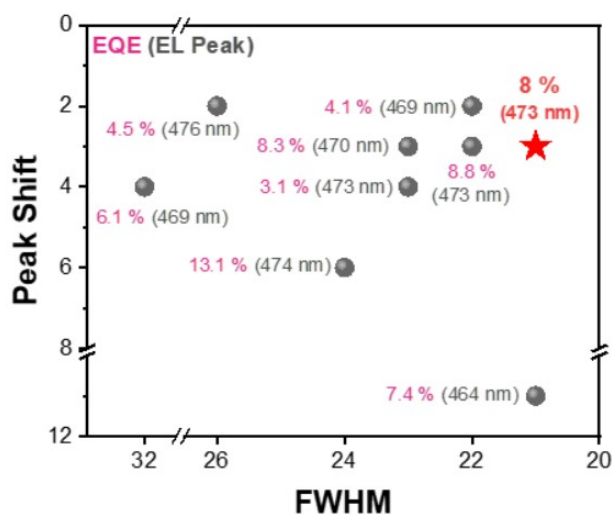
**Figure S5.** Schematic illustrating the interactions between PEA<sup>+</sup>, [PPN]<sup>+</sup>, and TFA<sup>-</sup>, and the mechanism for *n*-phase regulation. 'R' group denotes the phenethyl group (C<sub>6</sub>H<sub>5</sub>CH<sub>2</sub>CH<sub>2</sub>-).



**Figure S6.** SEM top-view images of perovskite films (a) without a TCTA layer and (b) on a TCTA layer. AFM images of the perovskite layer (c) without a TCTA layer and (d) on a TCTA layer.



**Figure S7.** Statistical LED performance plot of 22 devices satisfying EL peak shift conditions below 3 nm.



**Figure S8.** LED performance based on pure-blue emitting quasi-2D mixed halide perovskite. A 2D scatter plot correlating the spectral drift (Peak Shift) and emission linewidth (FWHM) of the corresponding devices. The red star highlights the optimized device from this work.

<b>Year</b>	<b>EL Peak<sub>0</sub> (nm)</b>	<b>FWHM<sub>0</sub> (nm)</b>	<b>EQE<sub>max</sub> (%)</b>	<b>DPeak (nm)</b>	<b>Ref.</b>
<b>2020</b>	473	23	8.8	3	[1]
<b>2021</b>	469	22	4.1	2	[2]
<b>2021</b>	473	23	3.1	4	[3]
<b>2022</b>	469	32	6.1	4	[4]
<b>2024</b>	477	29	4	-	[5]
<b>2024</b>	470	23	8.3	3	[6]
<b>2024</b>	464	21	7.4	> 10	[7]
	473	24	13.1	> 5	
<b>2025</b>	476	26	4.5	2	[8]
<b>2026</b>	<b>473</b>	<b>21</b>	<b>8</b>	<b>3</b>	<b>This work</b>

**Table S4.** Summary of the key parameters of pure-blue emitting quasi-2D mixed halide perovskite LEDs in Figure S8: electroluminescence (EL) characteristics, external quantum efficiency (EQE), and spectral stability ( $\Delta$ Peak).

## Reference

1. C. Wang, D. Han, J. Wang, Y. Yang, X. Liu, S. Huang, X. Zhang and S. Chang, *Nat. Commun.*, 2020, **11**, 6428.
2. K. Shen, H. Deng, Y. Shen, M. Guo, W. Cai, M. U. Ali, P. Liu, H.-L. Yip, Y.-Q. Li and J.-X. Tang, *Adv. Funct. Mater.*, 2021, **31**, 2006736.
3. F. Zhang, X. Zhang, C. Wang, M. Sun, X. Luo, Y. Yang, S. Chang, D. Zhang, *et al.*, *Nano Energy*, 2021, **79**, 105486.
4. X. Bai, H. Li, Y. Peng, G. Dong, *et al.*, *J. Am. Chem. Soc.*, 2022, **144**, 18470–18478.
5. Z. Bao, S. Yu, X. Guo, *et al.*, *Chem. Eng. J.*, 2024, **482**, 148875.
6. M.-S. Kim, P. Sadhukhan and J.-M. Myoung, *Adv. Funct. Mater.*, 2024, **34**, 2309436.
7. S. Yuan, L. Dai, Y. Sun, F. Auras, Y. H. Zhou, R. Z. An, Y. Liu, C. Ding, C. Cassidy, X. Tang, S. C. Dong, H. B. Kang, K. Chen, X. Liu, Z. F. Ye, Y. Zhao, C. Adachi, L. S. Liao, N. C. Greenham, Y. Qi, S. D. Stranks, L. S. Cui and R. H. Friend, *Nat. Photonics*, 2024, **18**, 425–431.
8. P. Pang, Z. Zhang, B. Wang, T. Sheng and G. Xing, *Nanoscale*, 2025, **17**, 9541–9551.