Electronic Supplementary Information For:

Drastic performance improvement of indoor organic photovoltaics using novel laminated homojunction hole-transport layer

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Equivalent circuit model

The performance of the OPVs is often described with a single-diode equivalent circuit model, and

including one current source and two parasitic resistances, a shunt resistance (R_P) and a series resistance (R_S) under illumination. The R_P is related to the leakage current, recombination, *etc.*, and the R_S is originated from the resistive components of the device such as resistance of electrodes and bulk resistance of photoactive layers.

By using the Shockley Eq. [1,2], the circuit model under illumination can be formulated, the J_{SC} and the V_{OC} can be expressed as follows,

$$J_{SC} = -\frac{1}{1+\frac{R_S}{R_P}}\left[J_{ph} - J_0\left\{exp\left(\frac{|J_{SC}|\,R_S A}{\frac{nkT}{e}}\right) - 1\right\}\right] \text{----------- (1)}$$

$$V_{OC} = \frac{kT}{q}\ln\left\{1 + \frac{J_{ph}}{J_0}\left(1 - \frac{V_{OC}}{J_{ph}R_P A}\right)\right\} \approx \frac{kT}{q}\ln\left\{1 + \frac{J_{ph}}{J_0}\right\} \text{--------- (2)}$$

, where J_{ph} is the photo-current density, J_0 is the reverse saturation current density, n is the ideality factor, q is the elementary charge number (1.602 × 10^{-19} C), k is the Boltzmann constant (8.617 × 10^{-5} eV/K), T is temperature, and A is the area of the photoactive region. Also, when $R_P \gg R_S$ and $J_{ph} = J_{SC}$, Eq. (2) can be written as $V_{OC} \approx \frac{kT}{q}\ln\left\{1 + \frac{J_{ph}}{J_0}\right\}$, which seems to be independent of R_S and R_P. The R_SA and R_PA values were extracted from the inverse slope of the *J-V* characteristics under illumination in the range of 0.96 – 1.0 V and near 0 V (close to the J_{SC} point), respectively. The FF ($J_{max} \times V_{max}/J_{SC} \times V_{OC}$) can be shown as a function of the normalized V_{OC} ($v_{OC} = eV_{OC}/nkT$), normalized R_S ($r_S = R_S/R_{CH}$), and normalized R_P ($r_P = R_P/R_{CH}$), where the characteristic resistance (R_{CH}) is defined as $R_{CH} = V_{OC}/(J_{SC}A)$. The equation for the ideal FF_0 of the OPVs is expressed as follows:

$$FF_0 = \frac{v_{OC} - ln(v_{OC} + 0.72)}{v_{OC} + 1} \quad \text{– (3)}$$

where, R_S = 0 and R_P = ∞. However, owing to the parasitic resistance effects, the real FF value should deviate from the ideal FF_0, and thus, semi-empirical expressions with the parasitic effects are shown below:

$$FF_S = FF_S(1 - 1.1r_S) + 0.19r_S^2, \quad \left(0 \le r_S \le 0.4, \ {}^{1}/_{r_P} = 0\right) \quad \text{– (4)}$$

and,

$$FF_{SP} = FF_S\left\{1 - \frac{(v_{OC} + 0.7)FF_S}{v_{OC} \quad r_P}\right\}, \ \left(0 \le r_S + {}^{1}/_{r_P} \le 0.4\right) \quad \text{– (5).}$$

$$V_{OC} = \frac{E_{gqp}}{q} - \frac{kT}{q}\ln\left\{\frac{(1 - P_D)\gamma N_C^2}{P_D G}\right\} \text{------ (6)}$$

where E_{gap} is the energy difference between the HOMO-donor and LUMO-acceptor, q is the elementary charge, k is the Boltzmann constant, T is temperature in Kelvin, P_D is the dissociation probability of the electron (e)-hole (h) pairs, γ is the Langevin recombination constant, N_C is the effective density of states, and G is the generation rate of bound e-h pairs.

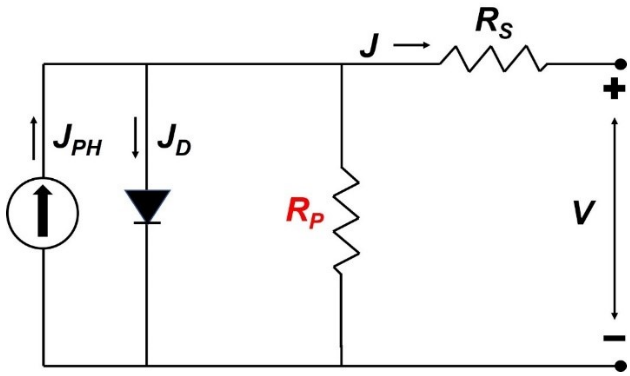

Fig. S1. Parasitic resistance effects based on the single-diode equivalent circuit model.

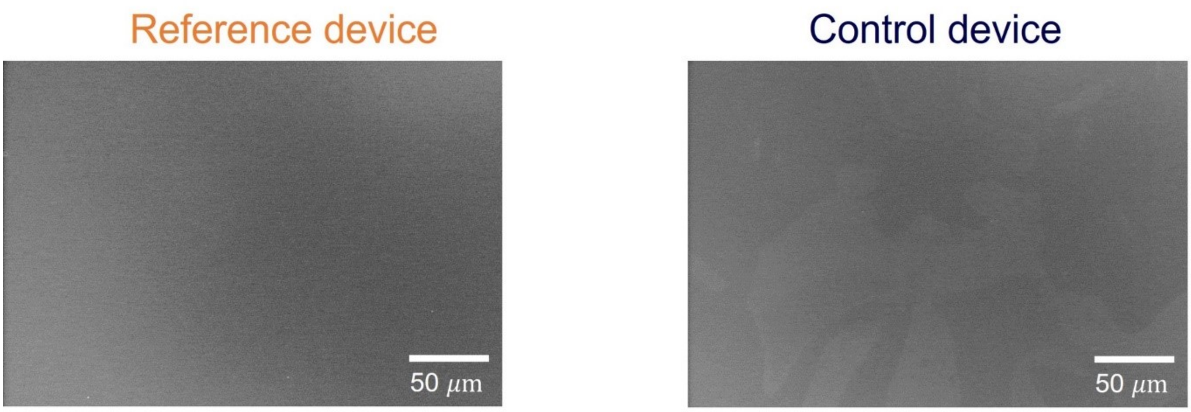

Fig. S2. The presence of PTQ10 is verified based on the top-down view of each SEM image.

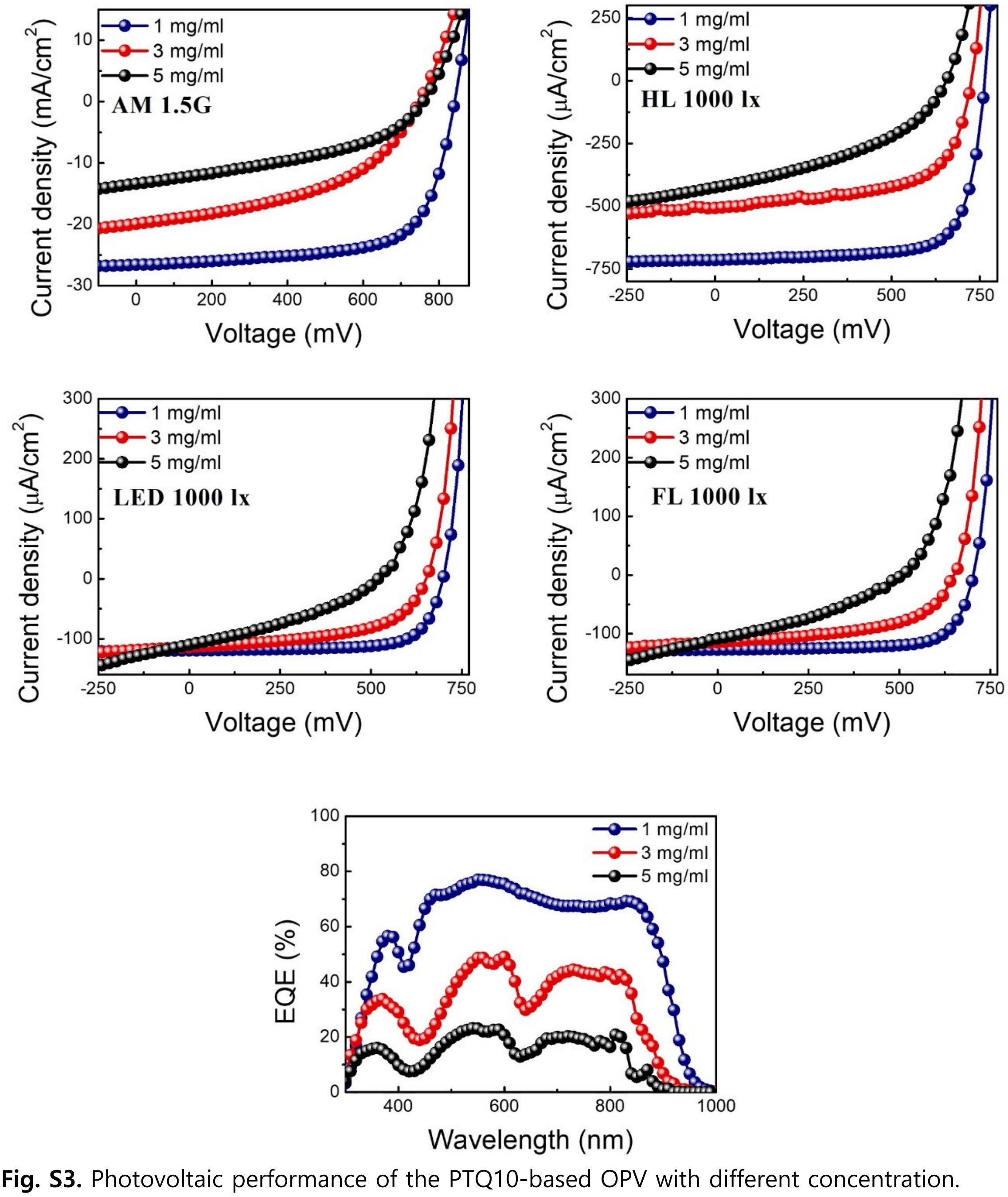

Fig. S3. Photovoltaic performance of the PTQ10-based OPV with different concentration.

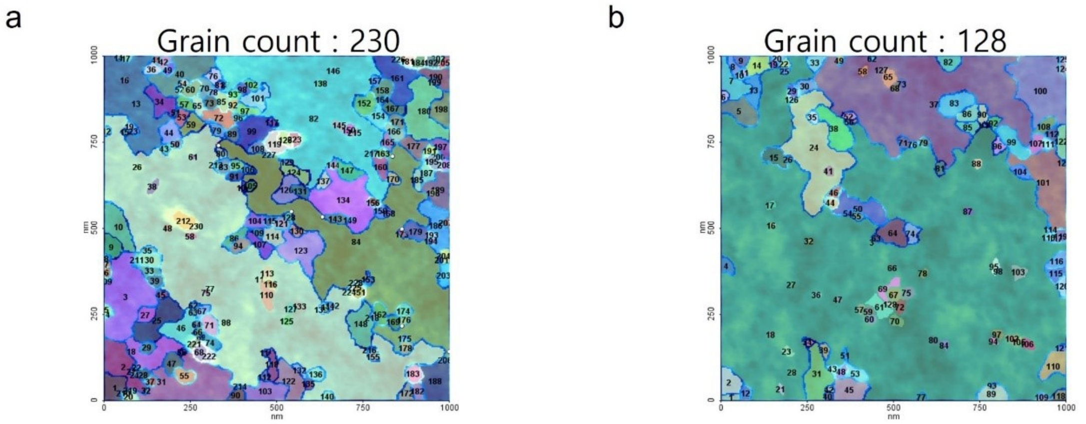

Fig. S4. 2D AFM grain-count drawings (a) PTQ10:Y6 and (b) PTQ10:Y6/PTQ10

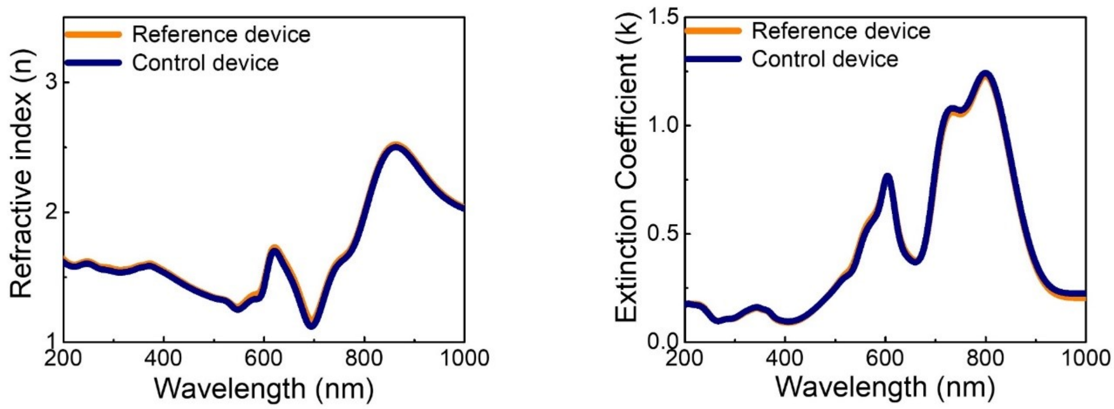

Fig. S5. Complex refractive index (n, k) of PTQ10 transport layers used for the finite-difference time-domain simulations.

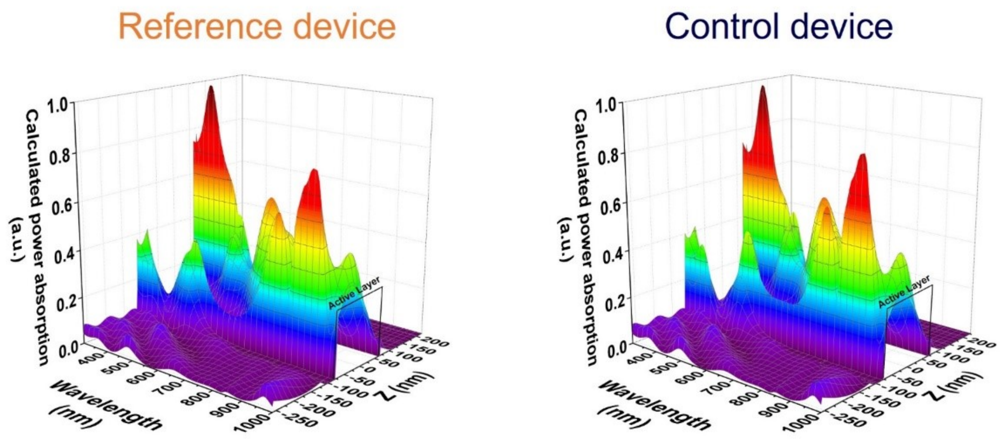

Fig. S6. Power-absorption profile of multicomponent photoactive blends obtained by the finite-difference time-domain method.

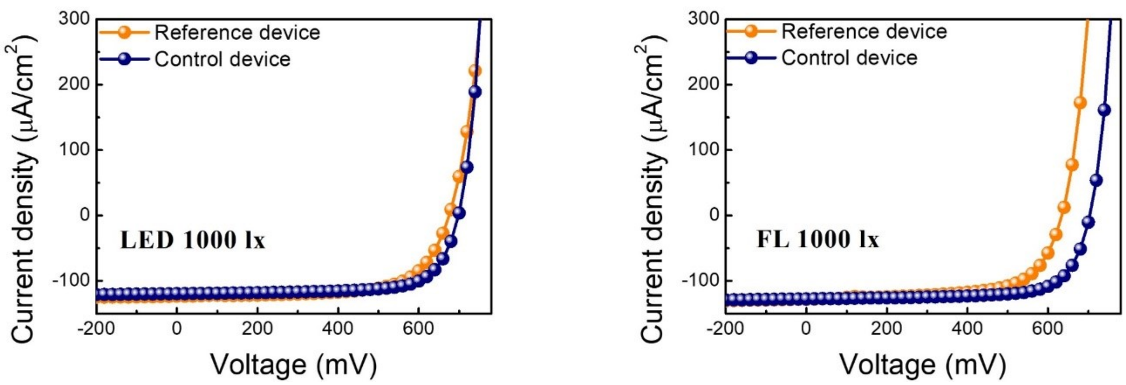

Fig. S7. Photovoltaic performance of Reference and Control devices under indoor (LED 1000 lx; FL 1000 lx) luminance.

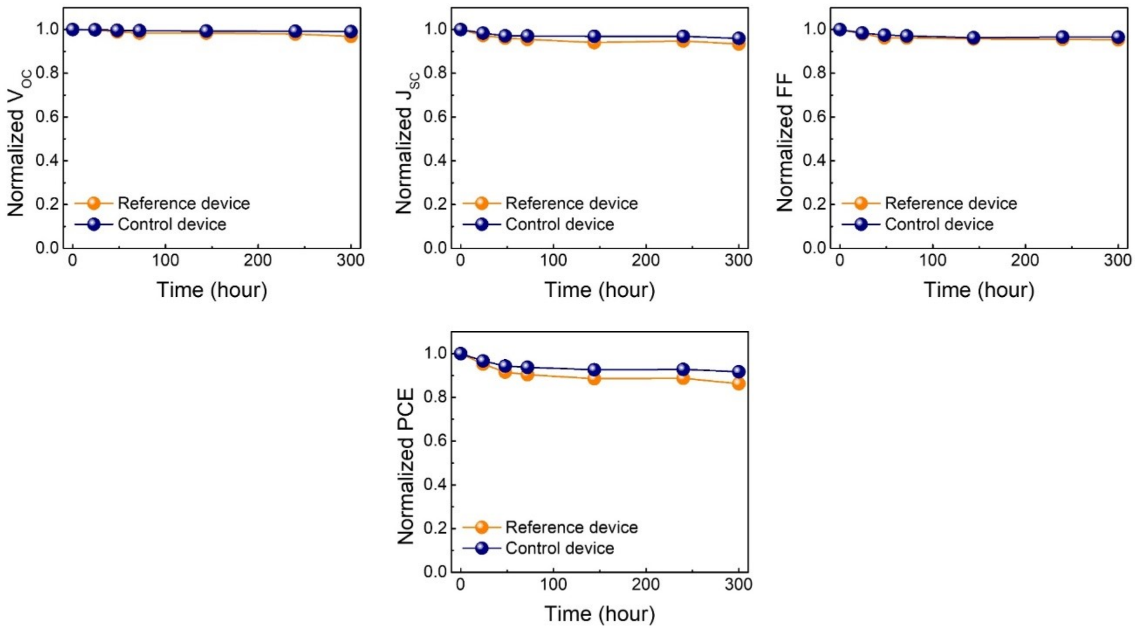

Fig. S8. Device stability of Reference and Control devices.

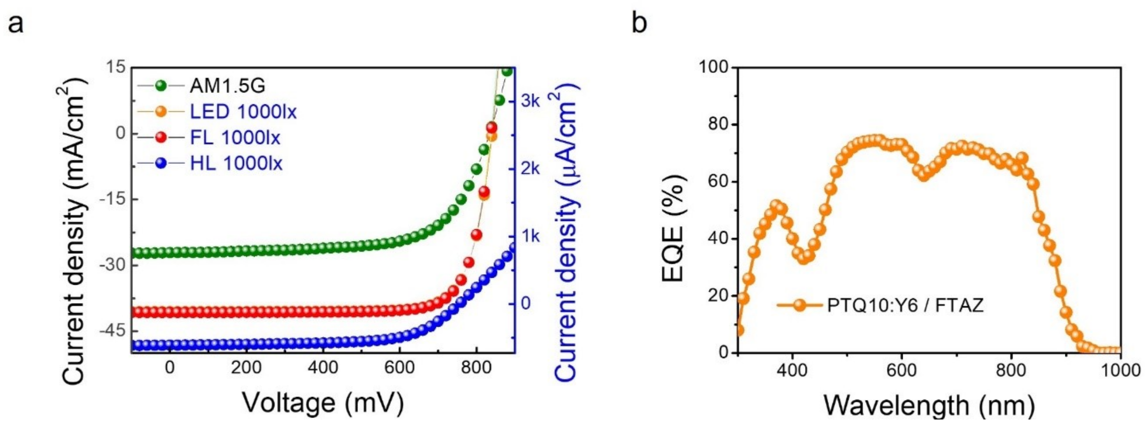

Fig. S9. (a) Photovoltaic performance of FTAZ-based device under outdoor and indoor (LED 1000 lx; FL 1000 lx; HL 1000 lx) luminance, (b) EQE spectra.

Table S1. Photovoltaic performance parameter of the PTQ10-based OPV with different concentration.

Light source	PTQ10 concentration (mg/ml)	V_{OC} (mV)	J_{SC} (1-sun: mA/cm²) (Indoor: μA/cm²)	FF (%)	PCE (%)
1-sun (100mW/cm²)	1	841 ± 11	26.9 ± 1.2	66.8 ± 1.1	15.1 ± 0.5
	3	740 ± 8	19.7 ± 0.3	45.1 ± 1.5	6.6 ± 0.4
	5	774 ± 18	15.8 ± 2.7	41.7 ± 1.7	5.1 ± 0.8
LED 1000 lx (0.23mW/cm²)	1	698 ± 2	119.5 ± 0.3	72.8 ± 0.1	26.4 ± 0.1
	3	651 ± 3	113.9 ± 0.1	54.8 ± 0.1	17.7 ± 0.1
	5	516 ± 5	110.2 ± 0.1	34.9 ± 0.4	8.6 ± 0.1
FL 1000 lx (0.27mW/cm²)	1	703 ± 2	126.0 ± 3.1	72.9 ± 0.3	23.9 ± 0.6
	3	649 ± 2	114.1 ± 0.9	54.0 ± 0.1	14.8 ± 0.2
	5	60 ± 7	104.9 ± 0.7	23.8 ± 0.6	0.6 ± 0.1
HL 1000 lx (7.0mW/cm²)	1	785 ± 8	685.2 ± 2.5	74.0 ± 0.3	5.7 ± 0.2
	3	726 ± 2	507.5 ± 0.2	61.4 ± 0.1	3.2 ± 0.1
	5	191 ± 4	538.6 ± 3.2	26.5 ± 0.5	0.4 ± 0.1

Table S2. In finite-difference time-domain (FDTD) simulation, the ideal current density of Reference and Control devices under halogen (HL) lighting.

Sample name	$J_{ph,Ideal}$	
	HL 500lx (μA/cm²)	HL 1000lx (μA/cm²)
Reference device	659.114	973.944
Control device	647.352	956.809

Table S3. Photovoltaic performance parameter of the PTQ10-based OPV under indoor (LED 1000lx; FL 1000lx) luminance.

Light source	Structure	V_{OC}	J_{SC}	FF	PCE

		(mV)	(μA/cm^2)	(%)	(%)
LED 1000 lx (0.23mW/cm^2)	Reference device	675 ± 2	123.4 ± 0.1	68.3 ± 0.3	23.7 ± 0.1
	Control device	698 ± 2	119.5 ± 0.3	72.8 ± 0.1	26.4 ± 0.1
FL 1000 lx (0.27mW/cm^2)	Reference device	680 ± 2	124.2 ± 2.0	67.5 ± 0.4	21.1 ± 0.4
	Control device	703 ± 2	126.0 ± 3.1	72.9 ± 0.3	23.9 ± 0.6

Table S4. Photovoltaic performance parameter of the FTAZ-based OPV under outdoor and indoor (LED 1000 lx; FL 1000 lx; HL 1000 lx) luminance.

Light source	V_{OC} **(mV)**	J_{SC} **(1-sun: mA/cm^2) (Indoor: μA/cm^2)**	**FF (%)**	**PCE (%)**
1-sun (100 mW/cm^2)	833 ± 2	27.1 ± 0.1	66.6 ± 0.2	15.0 ± 0.1
LED 1000 lx (0.23 mW/cm^2)	688 ± 4	120.7 ± 4.3	69.0 ± 0.8	24.9 ± 0.3
FL 1000 lx (0.27 mW/cm^2)	692 ± 2	125.4 ± 2.2	68.5 ± 0.9	22.0 ± 0.2
HL 1000 lx (7.0 mW/cm^2)	756 ± 3	650.5 ± 15.4	67.6 ± 0.1	4.7 ± 0.1

References

1 J. S. Goo, J. H. Lee, S. C. Shin, J. S. Park and J. W. Shim, *J. Mater. Chem. A*, 2018, **6**, 23464–23472.

2 B. Kippelen and J. L. Brédas, *Energy Environ. Sci.*, 2009, **2**, 251–261.