Supplementary information

30% efficient triple-cation perovskite solar cells under indoor illumination enabled by rare earth $EuCl_3$ doping

Jie Xu,[a] Sathy Harshavardhan Reddy,[a] Luigi Angelo Castriotta,[a] Suresh Kumar Podapangi,[a] Marco Luce,[b] Antonio Cricenti,[b] Aldo Di Carlo,[ab] and Thomas M. Brown*[a]

[a]*CHOSE (Centre for Hybrid and Organic Solar Energy), Department of Electronic Engineering, University of Rome Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy. E-mail: thomas.brown@uniroma2.it*

[b]*Istituto di Struttura della Materia (ISM-CNR), Via del Fosso del Cavaliere 100, 00133 Rome, Italy*

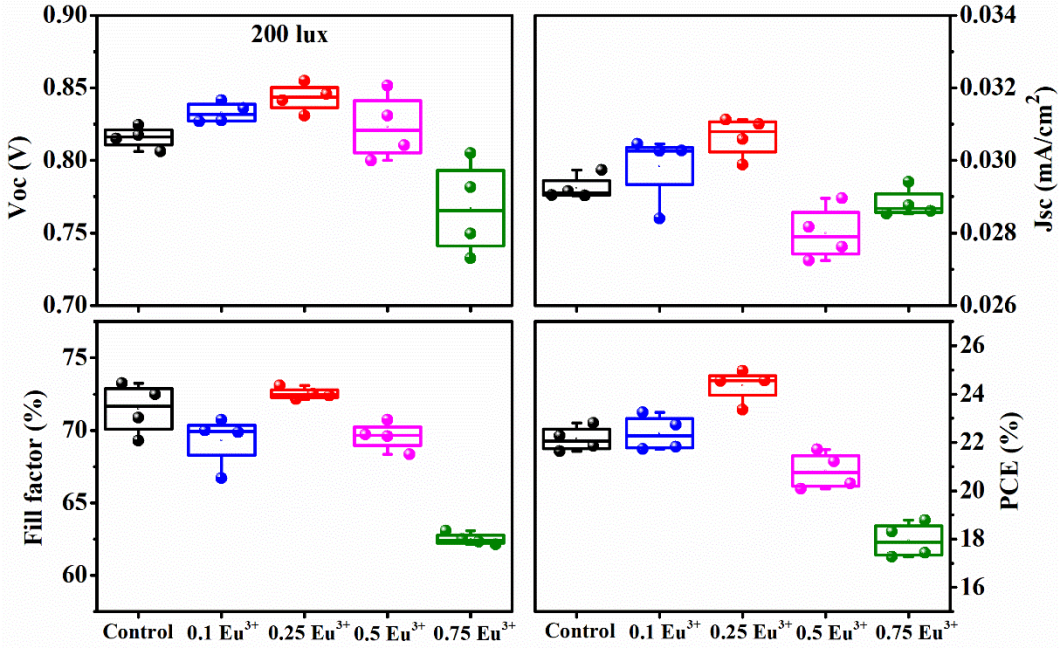

Figure S1. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio of $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 200 lx.

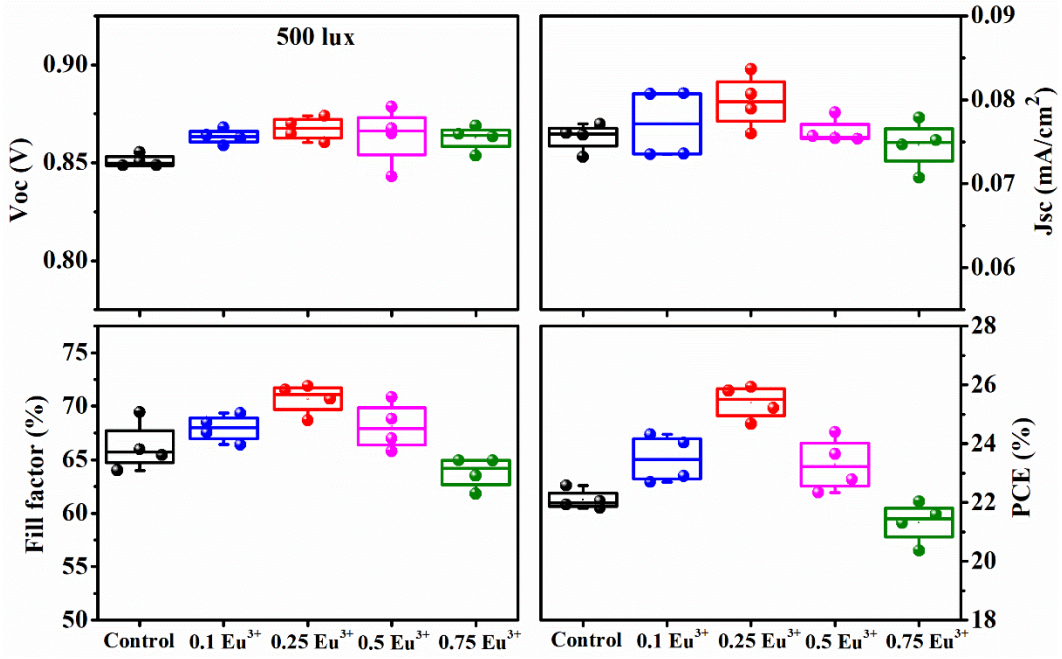

Figure S2. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio of $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 500 lx.

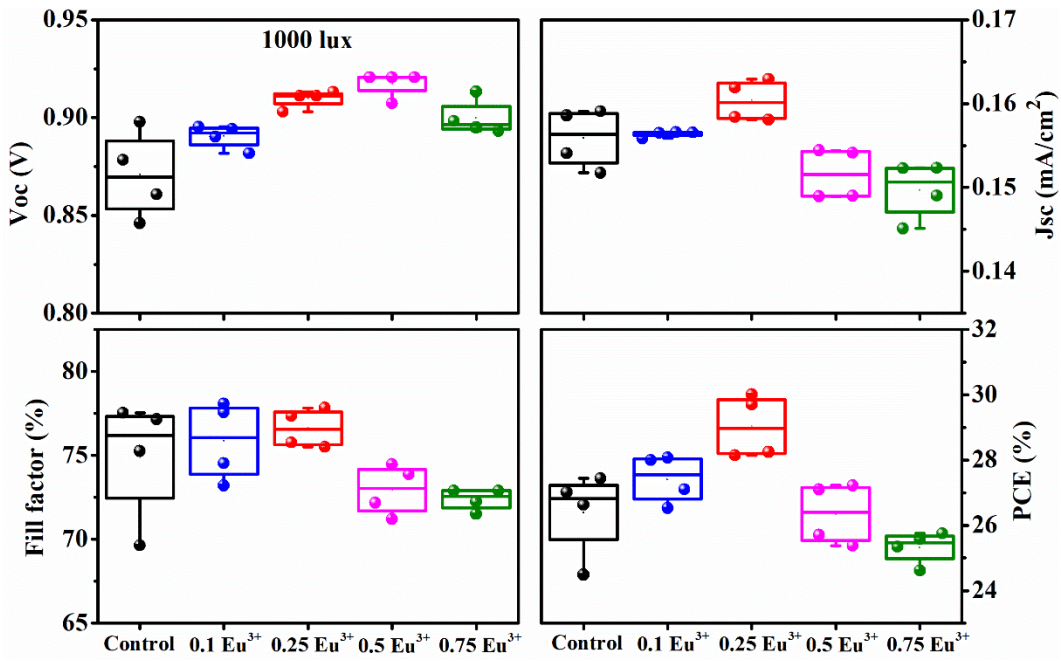

Figure S3. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio of $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 1000 lx.

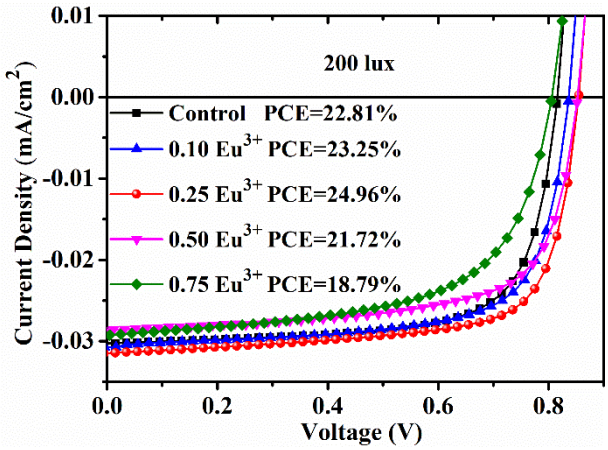

Figure S4. Current density-voltage (J-V) curves for the best performing devices measured under LED lamp at 200 lx.

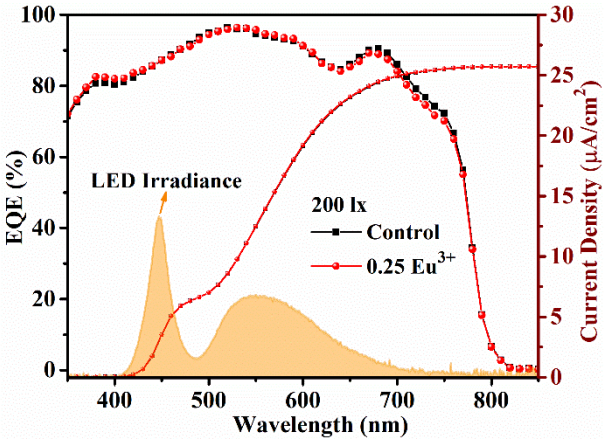

Figure S5. External quantum efficiency (EQE) curves and integrated J_{SC} under 200 lux for the best performing devices (control and 0.25 Eu^{3+}), and the irradiance of LED lamp at 200 lux (OSRAM P25 white light).

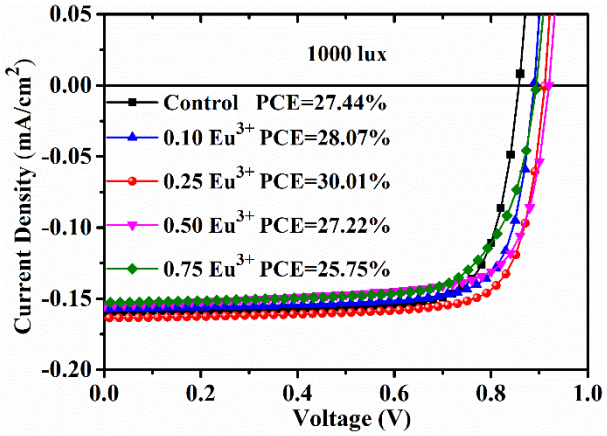

Figure S6. Current density-voltage (J-V) curves for the best performing devices

measured under LED lamp at 1000 lx.

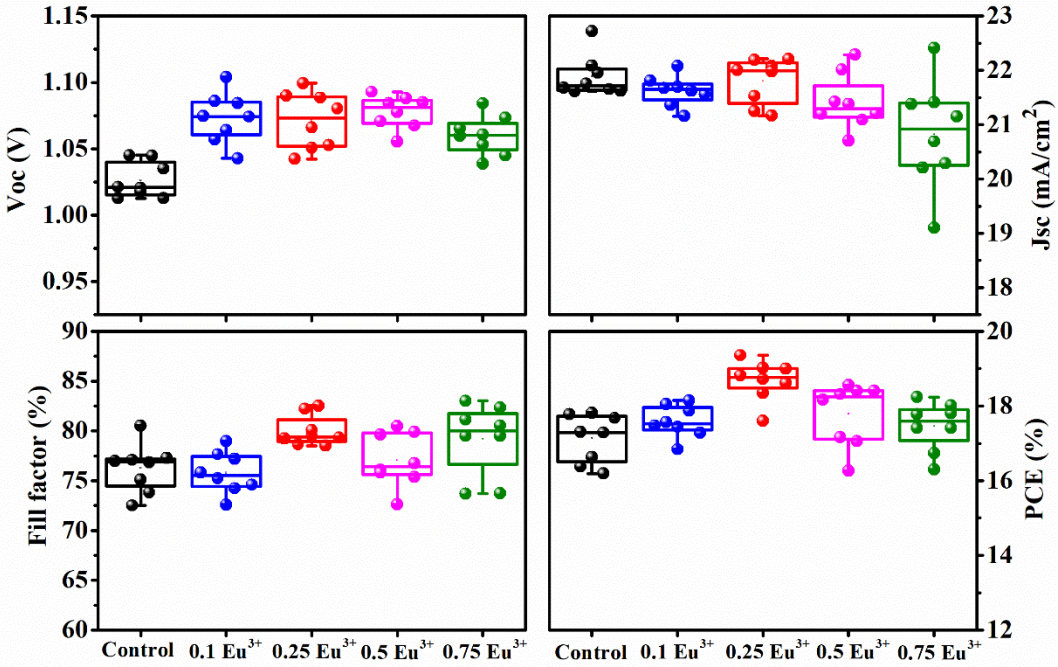

Figure S7. Photovoltaic parameters of perovskite solar cells incorporated with different ratio of $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under standard test conditions (STC, AM1.5G, 1000 W/m^2, 25 ˚C).

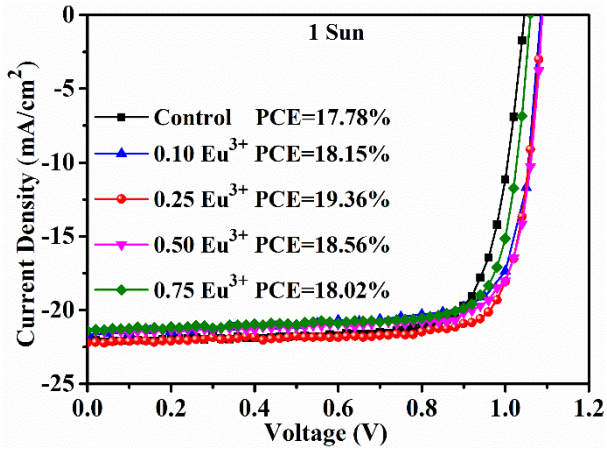

Figure S8. Current density-voltage (J-V) curves for the best performing devices measured under standard test conditions (STC, AM1.5G, 1000 W/m^2, 25 ˚C).

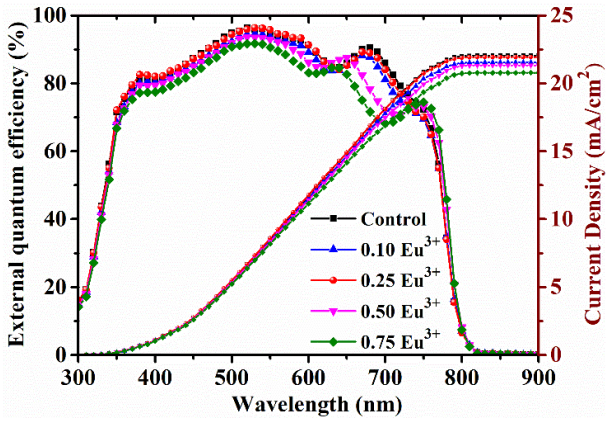

Figure S9. External quantum efficiency (EQE) spectra for the best performing cells were used to calculate the integrated current density (J_{SC}) convoluted with the AM1.5G spectrum.

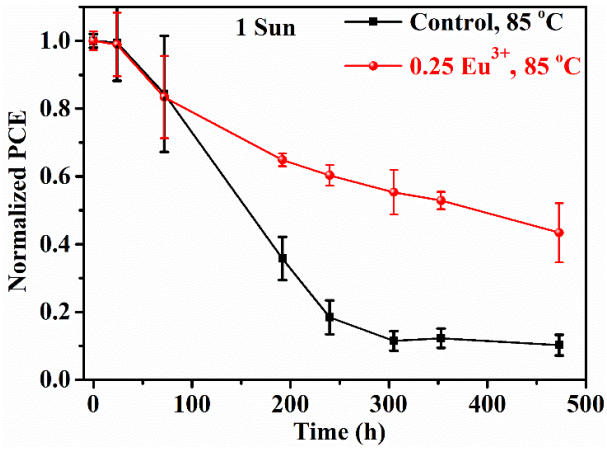

Figure S10. Power conversion efficiency (PCE) of unencapsulated cells measured at standard test conditions as a function of time for long-term stability tests carried out at 85 ˚C in ambient air (ISOS-D-2 test).

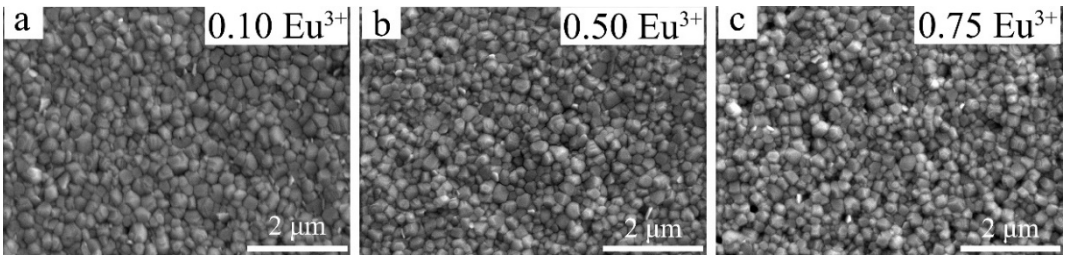

Figure S11. Scanning electron microscope (SEM) images of (a) 0.10 Eu^{3+}, (b) 0.50 Eu^{3+}, and (c) 0.75 Eu^{3+} incorporated perovskite films.

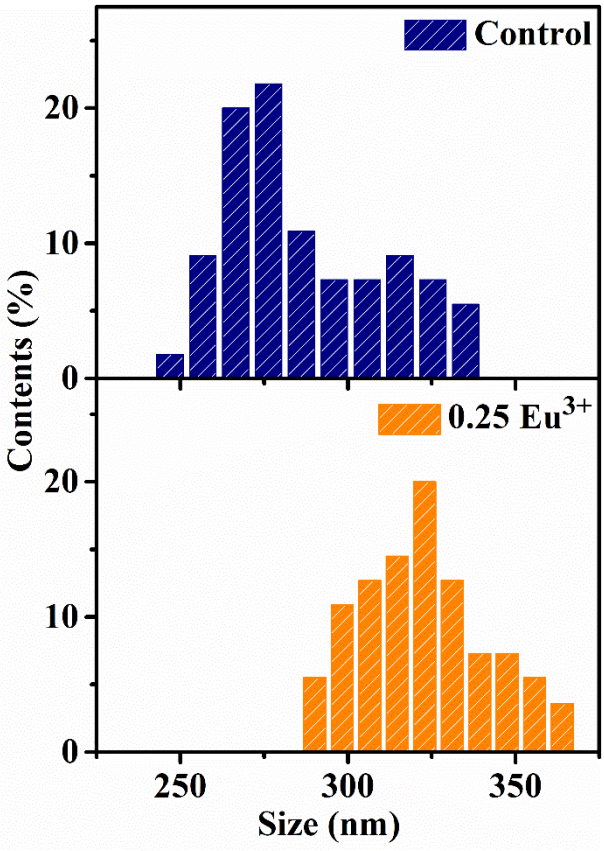

Figure S12. Grain size distribution of control (without $EuCl_3$ incorporated film) and 0.25 Eu^{3+} incorporated perovskite film.

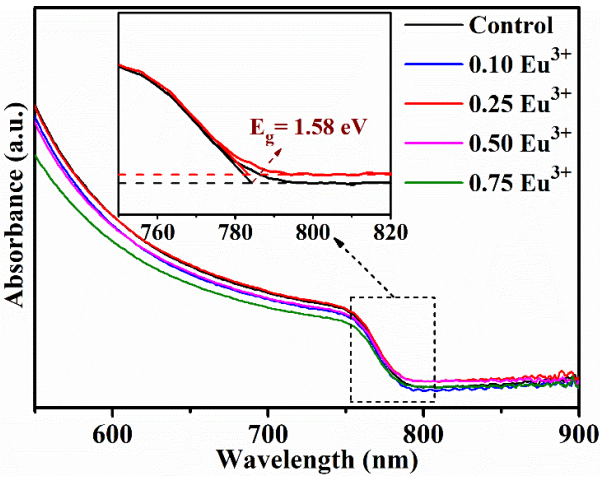

Figure S13. Absorption spectra, the inset is an enlarged image of the absorption edge, of different ratio of $EuCl_3$ incorporated Perovskite Films.

Table S1. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 200 lx.

	Voc [V]	Jsc [mA cm ^{2}]	FF [%]	PCE [%]
Control	0.816 ± 0.007 (0.815)	0.029 ± 0.001 (0.030)	71.474 ± 1.527 (72.483)	22.143 ± 0.452 (22.814)
0.10 Eu^{3+}	0.833 ± 0.006 (0.836)	0.030 ± 0.001 (0.030)	69.323 ± 1.553 (70.729)	22.381 ± 0.634 (23.247)
0.25 Eu^{3+}	0.843 ± 0.008 (0.855)	0.030 ± 0.001 (0.031)	72.532 ± 0.348 (72.507)	24.354 ± 0.605 (24.964)
0.50 Eu^{3+}	0.823 ± 0.020 (0.852)	0.028 ± 0.001 (0.028)	69.591 ± 0.852 (69.706)	20.830 ± 0.664 (21.717)
0.75 Eu^{3+}	0.767 ±0.028 (0.805)	0.029 ± 0.001 (0.029)	62.507 ± 0.351 (62.502)	17.947 ± 0.629 (18.788)

Table S2. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 500 lx.

	Voc [V]	Jsc [mA cm ^{2}]	FF [%]	PCE [%]
Control	0.851 ± 0.003 (0.855)	0.076 ± 0.001 (0.073)	66.217 ± 2.000 (69.450)	22.095 ± 0.292 (22.580)
0.10 Eu^{3+}	0.863 ± 0.003 (0.859)	0.077 ± 0.004 (0.081)	67.945 ± 1.094 (67.535)	23.487 ± 0.698 (24.312)
0.25 Eu^{3+}	0.867 ± 0.005 (0.860)	0.080 ± 0.003 (0.081)	70.701 ± 1.249 (71.903)	25.406 ± 0.500 (25.928)
0.50 Eu^{3+}	0.864 ± 0.013 (0.879)	0.076 ± 0.001 (0.075)	68.116 ± 1.918 (70.859)	23.292 ± 0.792 (24.392)
0.75 Eu^{3+}	0.863 ± 0.006 (0.869)	0.075 ± 0.003 (0.075)	63.802 ± 1.279 (64.926)	21.325 ± 0.611 (22.038)

Table S3. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under illumination from an LED lamp at 1000 lx.

	Voc [V]	Jsc [mA cm ^{2}]	FF [%]	PCE [%]
Control	0.871 ± 0.019 (0.861)	0.156 ± 0.003 (0.159)	74.895 ± 3.151 (77.147)	26.393 ± 1.138 (27.437)
0.10 Eu^{3+}	0.890 ± 0.005 (0.890)	0.156 ± 0.001 (0.157)	75.844 ± 2.042 (77.568)	27.424 ± 0.643 (28.072)
0.25 Eu^{3+}	0.910 ± 0.004 (0.911)	0.160 ± 0.002 (0.163)	76.618 ± 0.994 (77.834)	29.028 ± 0.839 (30.012)
0.50 Eu^{3+}	0.917 ± 0.006 (0.920)	0.152 ± 0.003 (0.154)	72.932 ± 1.300 (73.874)	26.350 ± 0.821 (27.224)
0.75 Eu^{3+}	0.900 ± 0.008 (0.893)	0.150 ± 0.003 (0.152)	72.383 ± 0.570 (72.888)	25.322 ± 0.435 (25.749)

Table S4. Photovoltaic parameters for triple cation perovskite solar cells incorporation with different ratio $EuCl_3$ (0.1, 0.25, 0.5, and 0.75 mM, abbreviated as 0.1, 0.25, 0.5, and 0.75 Eu^{3+}), measured under standard test conditions (AM1.5G, 1000 W/m^2, 25 °C).

	Voc [V]	Jsc [mA cm ^{2}]	FF [%]	PCE [%]
Control	1.03 ± 0.01 (1.04)	21.89 ± 0.35 (22.09)	76.27 ± 2.30 (76.98)	17.13 ± 0.61 (17.78)
0.10 Eu^{3+}	1.07 ± 0.02 (1.09)	21.62 ± 0.26 (21.68)	75.79±1.94 (77.21)	17.59± 0.40 (18.15)
0.25 Eu^{3+}	1.07 ± 0.02 (1.09)	21.80 ± 0.40 (22.21)	80.01 ± 1.44 (80.08)	18.69 ± 0.50 (19.36)
0.50 Eu^{3+}	1.08 ± 0.01 (1.09)	21.41 ± 0.480 (21.43)	77.08 ± 2.54 (79.63)	17.79 ± 0.80 (18.56)
0.75 Eu^{3+}	1.06 ± 0.01 (1.06)	20.83 ± 0.93 (21.38)	79.19 ± 3.36 (79.51)	17.46 ± 0.61 (18.02)

Table S5. Key parameters of the Normalized time-resolved PL (TRPL) curves obtained from biexponential function fitting line.

	A_1	τ_1 (ns)	A_2	τ_2 (ns)	τ_{avg} (ns)
Control	0.27	233.7	0.60	1.8	229.7
0.25 Eu^{3+}	0.30	348.6	0.59	1.8	345.2