Supporting Information

Realizing Efficient Photoluminescence Spectral Modulation via Sb^{3+}/Ln^{3+} co-doped Doping in $Cs_2NaInCl_6$ Double Perovskites

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Table S1. Tb^{3+} ion content for Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ samples studied using inductively coupled plasma emission spectrometry. Sb^{3+} % and Tb^{3+} % is calculated following the equation ([Sb]/[In+Sb]) ×100% and ([Tb]/[In+Sb])×100%, respectively.

Samples	Precursor		Product	
	Sb / mmol	Tb / mmol	Sb^{3+} %	Tb^{3+} %
Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$	0.05	0	0.34	0
	0.05	0.5	0.43	0.79
	0.05	1.0	0.37	1.76
	0.05	1.5	0.31	2.48
	0.05	2.0	0.31	3.70
	0.05	2.5	0.23	5.49

Table S2. Ho^{3+} ion content for Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ samples studied using inductively coupled plasma emission spectrometry. Sb^{3+} % and Ho^{3+} % is calculated following the equation ([Sb]/[In+Sb]) ×100% and ([Ho]/[In+Sb])×100%, respectively.

Samples	Precursor		Product	
	Sb / mmol	Ho / mmol	Sb^{3+} %	Ho^{3+} %
Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$	0.05	0	0.34	0
	0.05	0.5	0.24	0.29
	0.05	1.0	0.22	1.50
	0.05	1.5	0.18	3.60
	0.05	2.0	0.20	7.25
	0.05	2.5	0.21	11.13

Table S3. The TRPL lifetimes monitored at 440 and 547 nm and energy transfer efficiency (η_{ET}) for $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: $y$$Tb^{3+}$ samples.

Samples	Lifetime (*440 nm*) / μs	Lifetime (*547 nm*) / ms	η_{ET} / %
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$	1.02	—	—
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 0.5 mmol Tb^{3+}	1.02	6.34	0.2%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 1.0 mmol Tb^{3+}	1.00	6.35	2.3%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 1.5 mmol Tb^{3+}	0.95	6.60	7.0%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 2.0 mmol Tb^{3+}	0.93	6.62	9.2%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 2.5 mmol Tb^{3+}	0.91	6.64	11.0%

Table S4. The TRPL lifetimes monitored at 440 and 655 nm and energy transfer efficiency (η_{ET}) for $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: $z$$Ho^{3+}$ samples.

Samples	Lifetime (*440 nm*) / μs	Lifetime (*655 nm*) / ms	η_{ET} / %
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$	1.02	—	—
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 0.5 mmol Ho^{3+}	0.95	2.96	6.7%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 1.0 mmol Ho^{3+}	0.92	4.24	10.3%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 1.5 mmol Ho^{3+}	0.82	4.82	20.0%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 2.0 mmol Ho^{3+}	0.77	5.20	24.6%
$Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: 2.5 mmol Ho^{3+}	0.75	5.29	27.0%

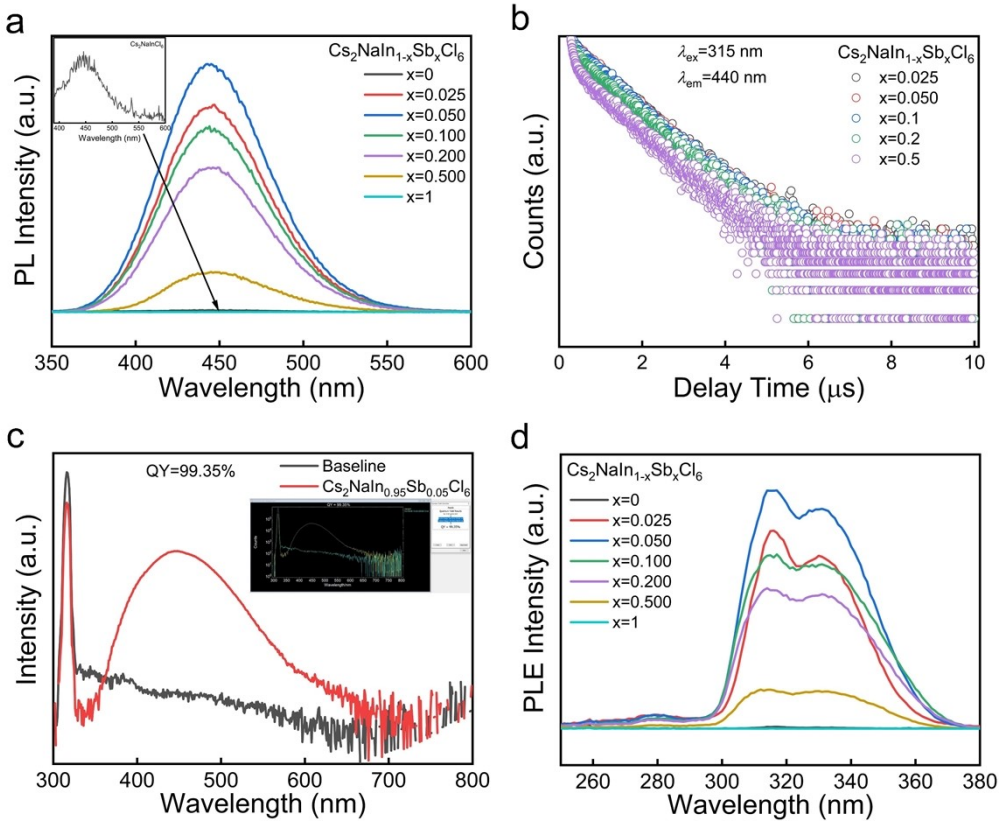

Figure S1. a) The PL spectra, b) TRPL decay curves, c) PLQY curves, and d) PLE spectra monitored at 440 nm of $Cs_2NaIn_{1-x}Sb_xCl_6$ DPs.

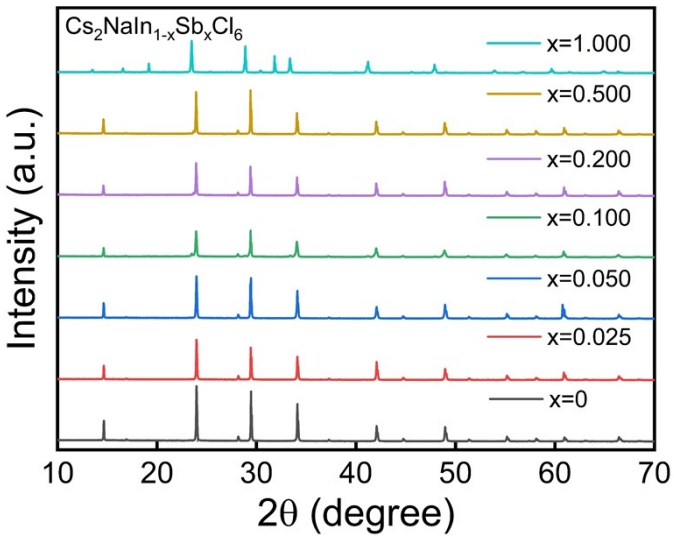

Figure S2. XRD patterns of the $Cs_2NaIn_{1-x}Sb_xCl_6$ crystals with different Sb^{3+} ion concentration.

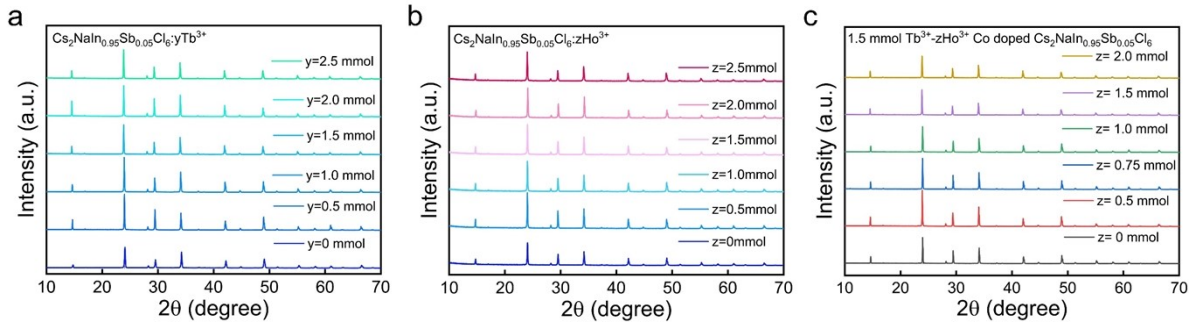

Figure S3. XRD patterns of a) the $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: $y$$Tb^{3+}$ crystals with different Tb^{3+} ion concentrations, b) the $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: $z$$Ho^{3+}$ crystals with different Ho^{3+} ion concentrations, and c) the Tb^{3+} and Ho^{3+} co-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystals with different Ho^{3+} ion concentrations.

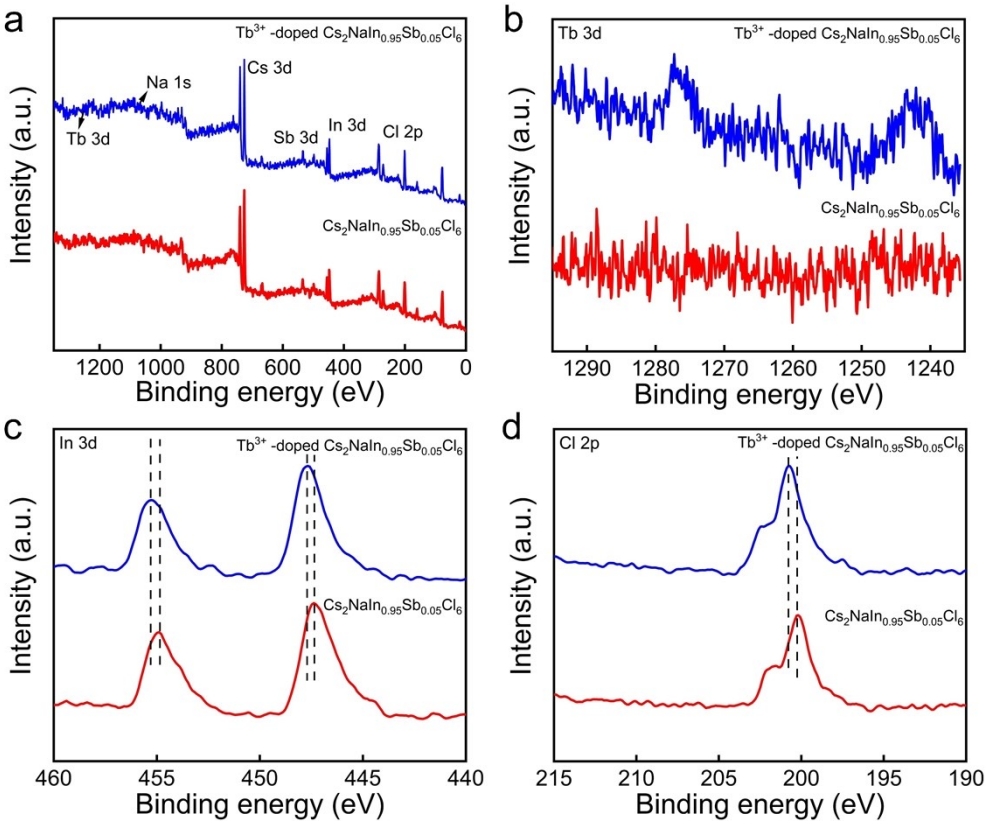

Figure S4. a) The XPS spectroscopy based on undoped and 1.5 mmol Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystal. b) the XPS pattern for Tb 3d, c) In 3d, and d) Cl 2p of the undoped and 1.5 mmol Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystal.

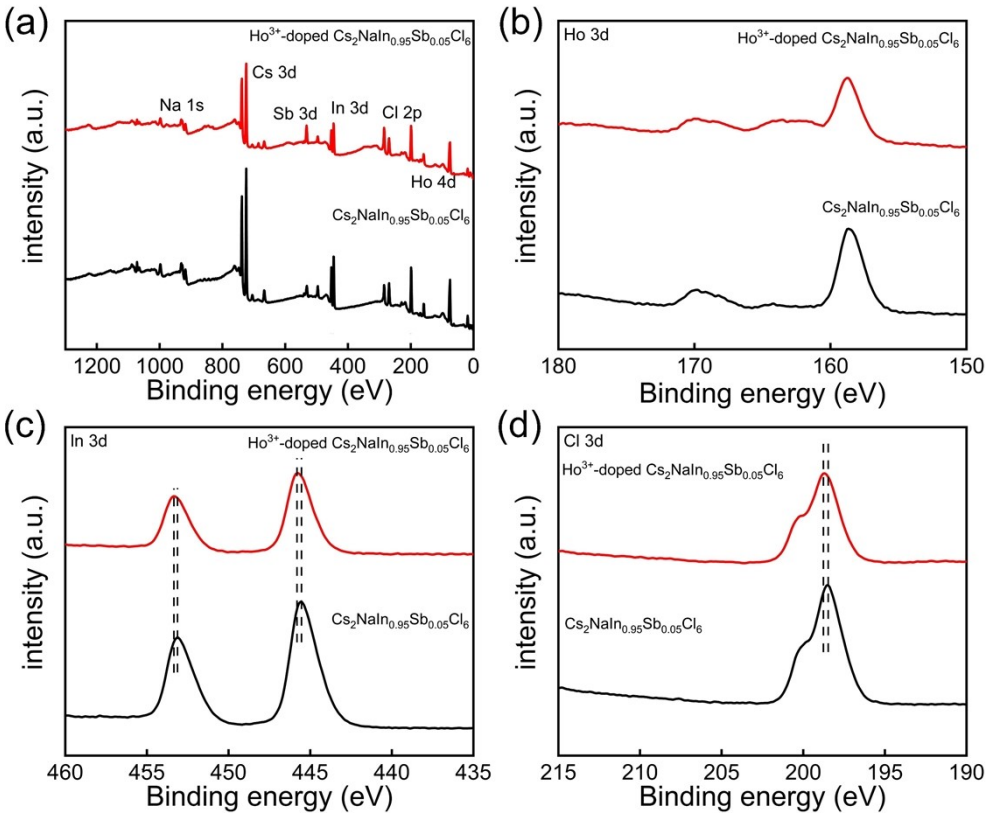

Figure S5. a) The XPS spectroscopy based on undoped and 2.0 mmol Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystal. b) the XPS pattern for Ho 3d, c) In 3d, and d) Cl 2p of the undoped and 2.0 mmol Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystal.

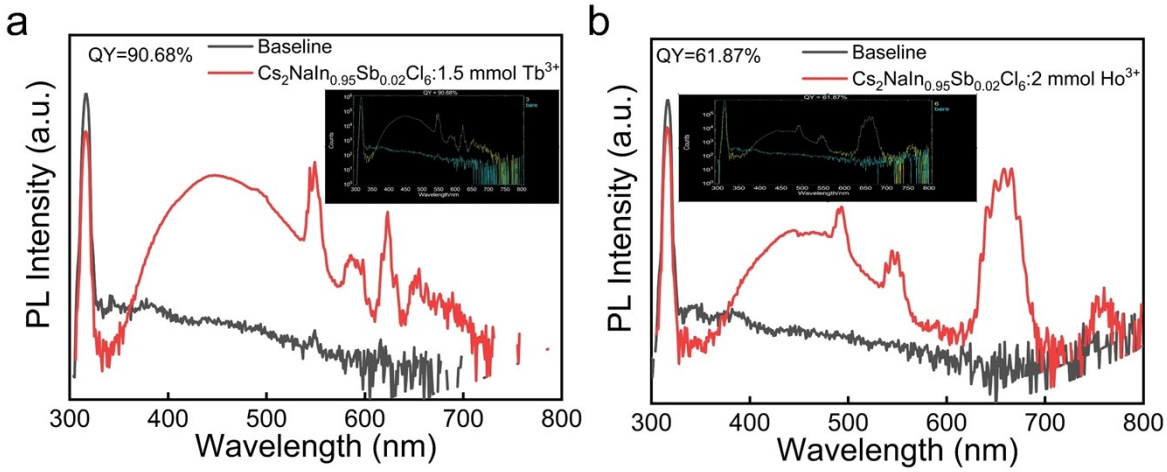

Figure S6. The PLQY of a) 1.5 mmol Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: crystal, and b) 2.0 mmol Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystal.

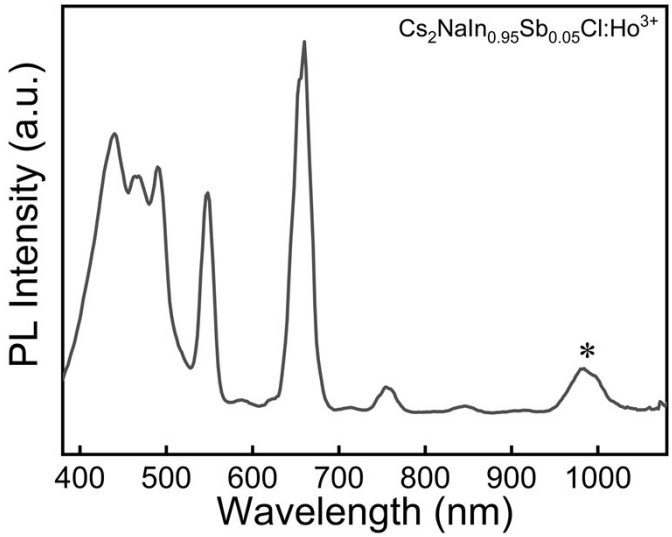

Figure S7. The near-infrared emission of 2.0 mmol Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$.

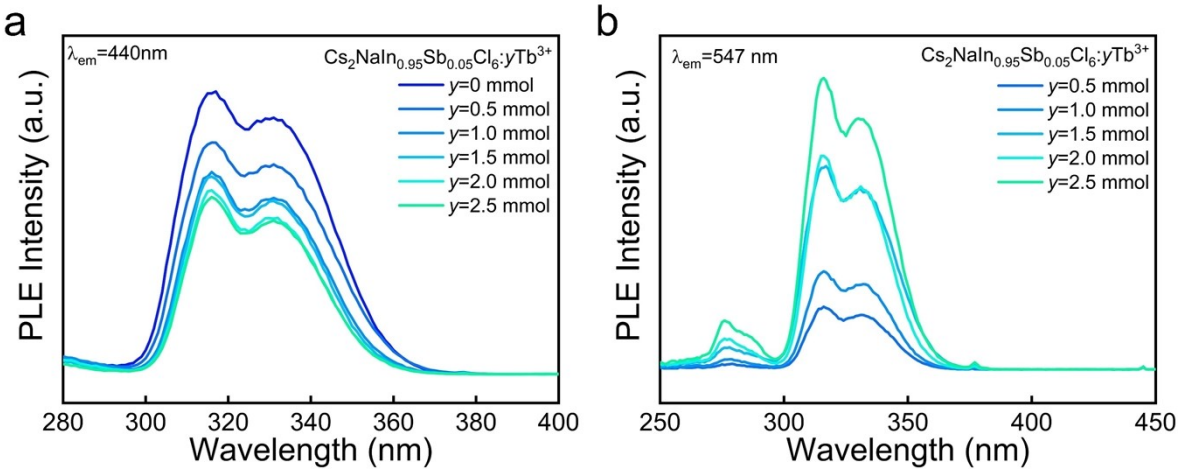

Figure S8. PLE spectra of $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$:$y$$Tb^{3+}$ a) emission wavelength at 440 nm, and b) emission wavelength at 547 nm.

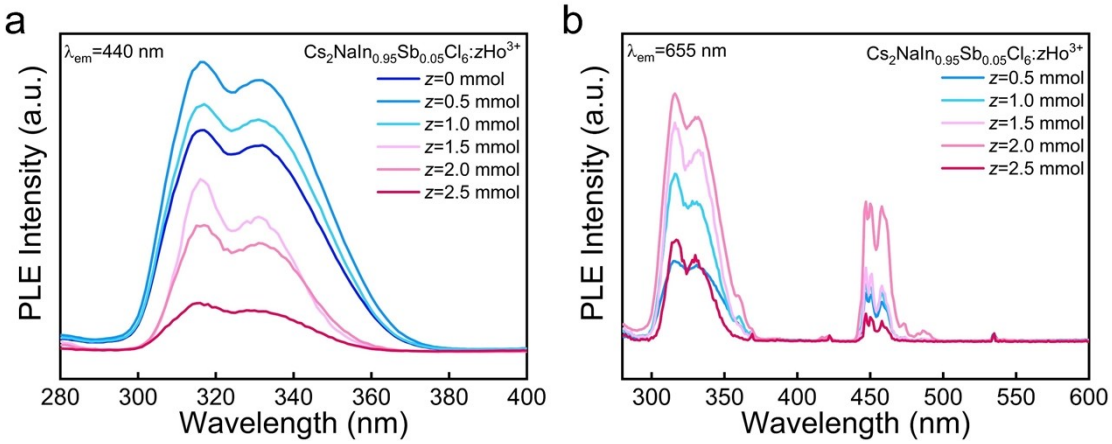

Figure S9. PLE spectra of $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$:$zHo^{3+}$ a) emission wavelength at 440 nm, and b) emission wavelength at 655 nm.

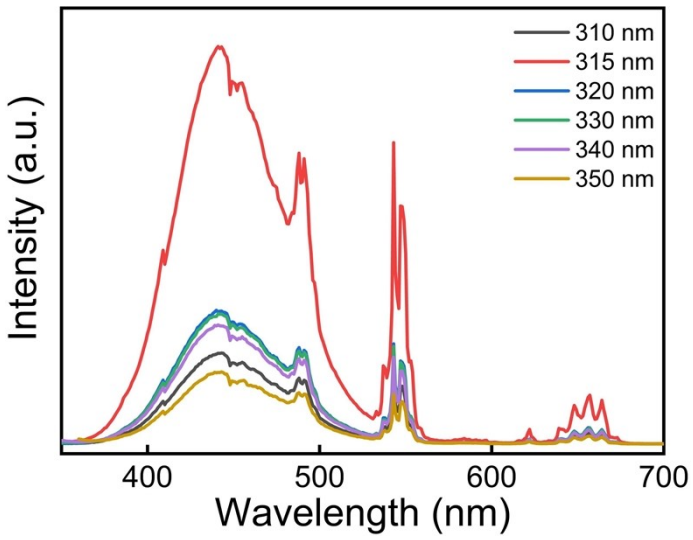

Figure S10. The PL spectra of $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$:1.5 mmol Tb^{3+} crystal at different excitation wavelengths.

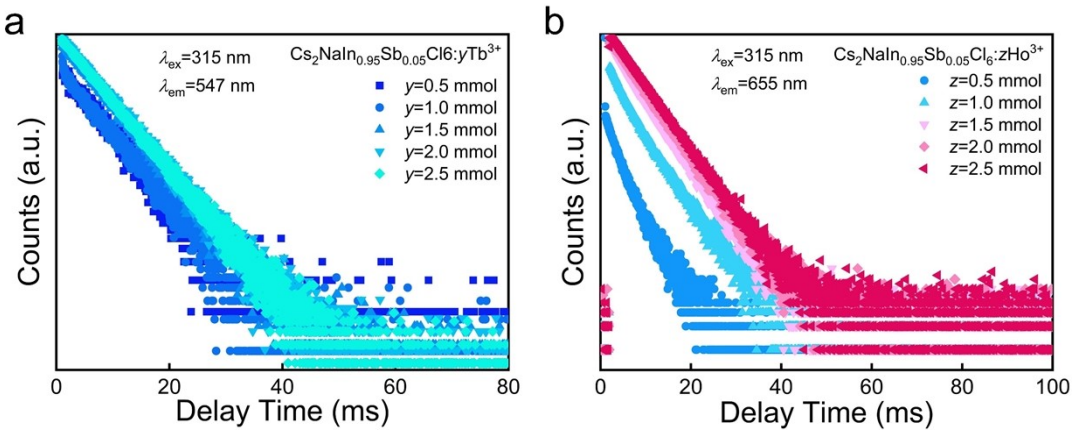

Figure S11. The TRPL curves of a) $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: yTb^{3+} crystals at 547 nm, and b) $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$: zHo^{3+} crystals at 655 nm.

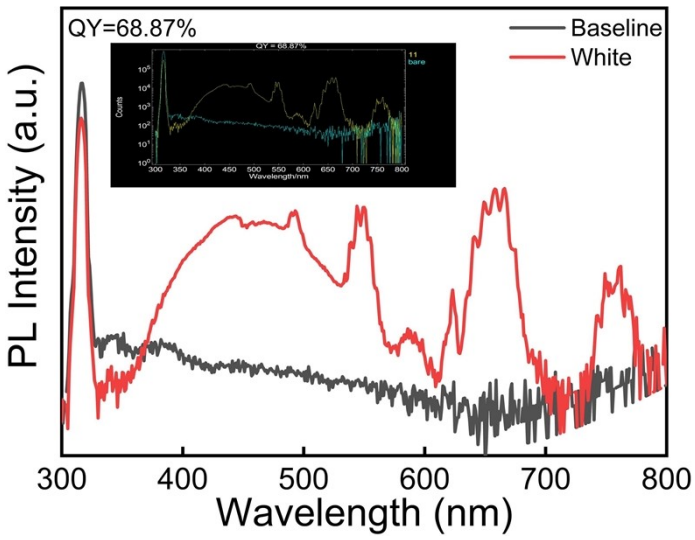

Figure S12. The PLQY curve of Tb^{3+} and Ho^{3+} co-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ sample.

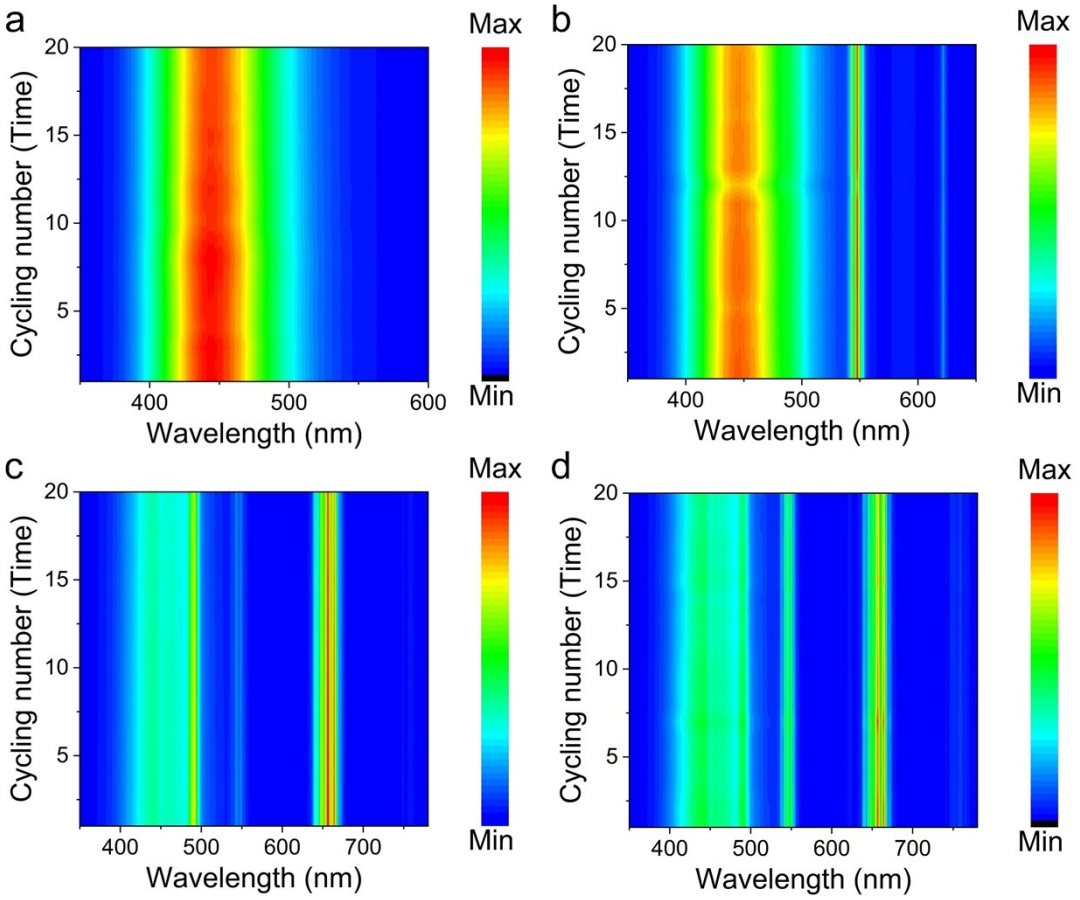

Fig S13. The luminescence thermal stability of 20 cold and hot cycles. The PL spectra of a) $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, b) Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, c) Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, and d) Tb^{3+} and Ho^{3+} co-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ samples.

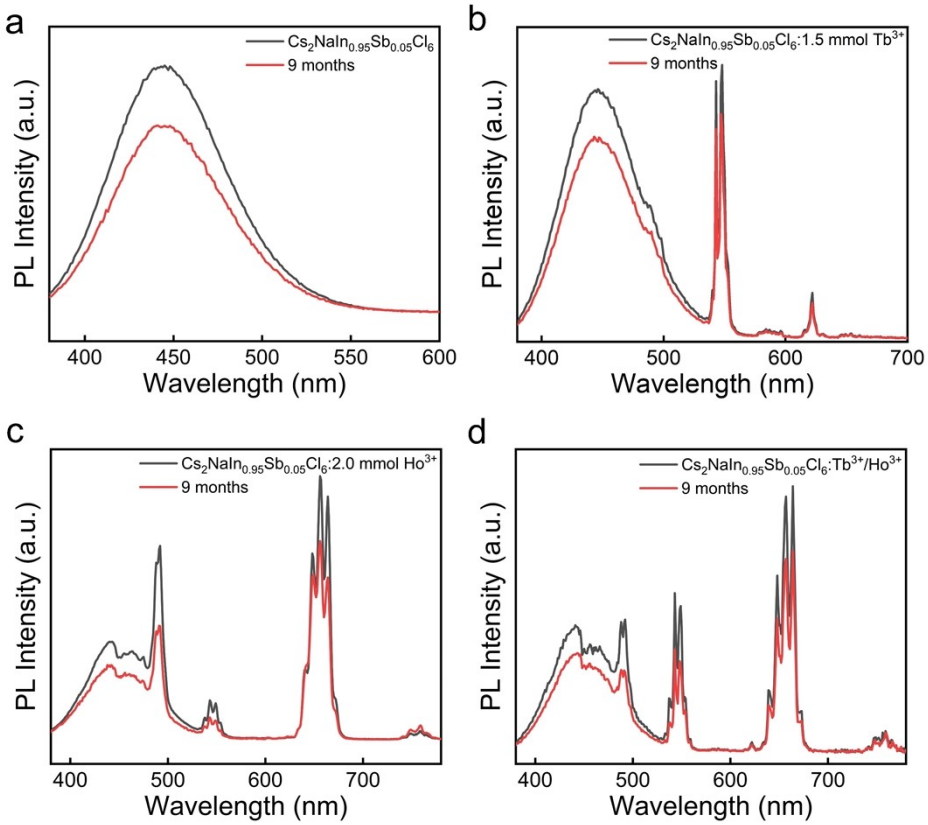

Figure S14. The humidity stability of the prepared phosphor storage in the air for 270 days. The PL spectra of a) $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, b) Tb^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, c) Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$, and d) Tb^{3+}/Ho^{3+} co-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ samples.

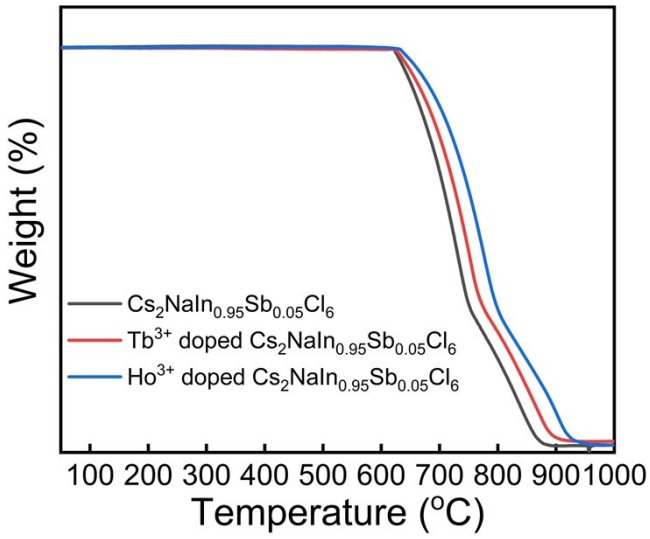

Figure S15. TGA curves of free-doped, Tb^{3+}-doped, and Ho^{3+}-doped $Cs_2NaIn_{0.95}Sb_{0.05}Cl_6$ crystals

under N_2 atmosphere in the temperature range of 25-1000 °C at a heating rate of 10 °C min^{-1}.