Supporting Information

Strong sensitivity enhancement in lifetime-based luminescence thermometry by co-doping of $SrTiO_3:Mn^{4+}$ nanocrystals with trivalent lanthanide ions

W. M. Piotrowski[1], K. Trejgis[1], M. Dramicanin[2], L. Marciniak[1]*

[1]Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Okólna 2, 50-422 Wroclaw, Poland

[2]Vinča Institute of Nuclear Sciences - National Institute of the Republic of Serbia, University of Belgrade, P.O. Box 522, Belgrade 11001, Serbia

* corresponding author: *l.marciniak@intibs.pl*

KEYWORDS luminescent thermometry, emission decays, lanthanides, $SrTiO_3$, luminescence

The average lifetime of the excited states were calculated with the equation Eq. S1:

$$\tau_{avr} = \frac{A_1\tau_1^{\,2} + A_2\tau_2^{\,2}}{A_1\tau_1 + A_2\tau_2} \qquad \text{(Eq. S1)}$$

where: τ_1, τ_2 – the average time, which is in accordance with the relation $\tau = t \cdot \ln(2)$ and A_1, A_2 – amplitude, which are the parameters of the doubleexponential function:

$$y = y_0 + A_1 \cdot \exp(-\frac{x}{t_1}) + A_2 \cdot \exp(-\frac{x}{t_2}) \qquad \text{(Eq. S2)}$$

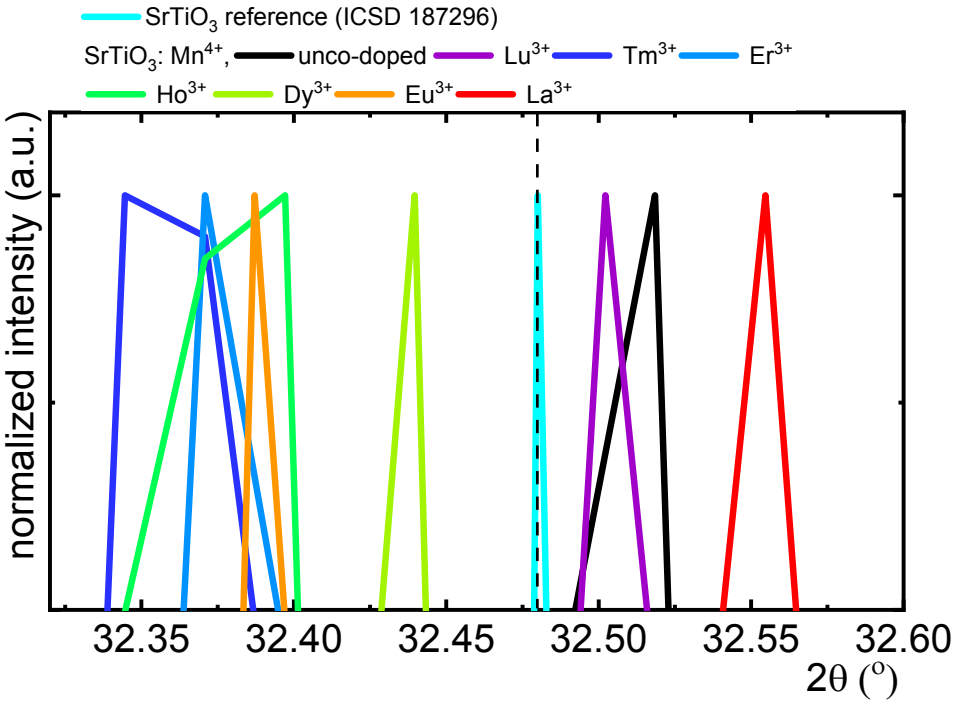

Figure S1. The zoom of the maximum of X-ray diffraction patterns of $SrTiO_3$:Mn^{4+} with different Ln^{3+} dopants.

Table S1. Shannon effective ionic radii of $SrTiO_3$ lattice and dopant ions.

Site	Coordination number (CN)	Shannon effective ionic radii (EIR) (pm)							
			Ti^{4+}			Mn^{4+}		Ti^{3+}	
octahedral	VI (6-fold)		60.5			53		67	
		Sr^{2+}	Lu^{3+}	Tm^{3+}	Er^{3+}	Ho^{3+}	Dy^{3+}	Eu^{3+}	La^{3+}
preferred	VIII/X (8-/10-fold)	-	97.7 (VIII)	99.4 (VIII)	100.4 (VIII)	101.5 (VIII)	102.7 (VIII)	106.6 (VIII)	127 (X)
cuboctahedral	XII (12-fold)	144	120.4 [e]	122.4 [e]	123.4 [e]	123.4 [e]	125.5 [e]	129.5 [e]	136

e – extrapolated linearly (in the all cases $R^2 > 0.9987$)

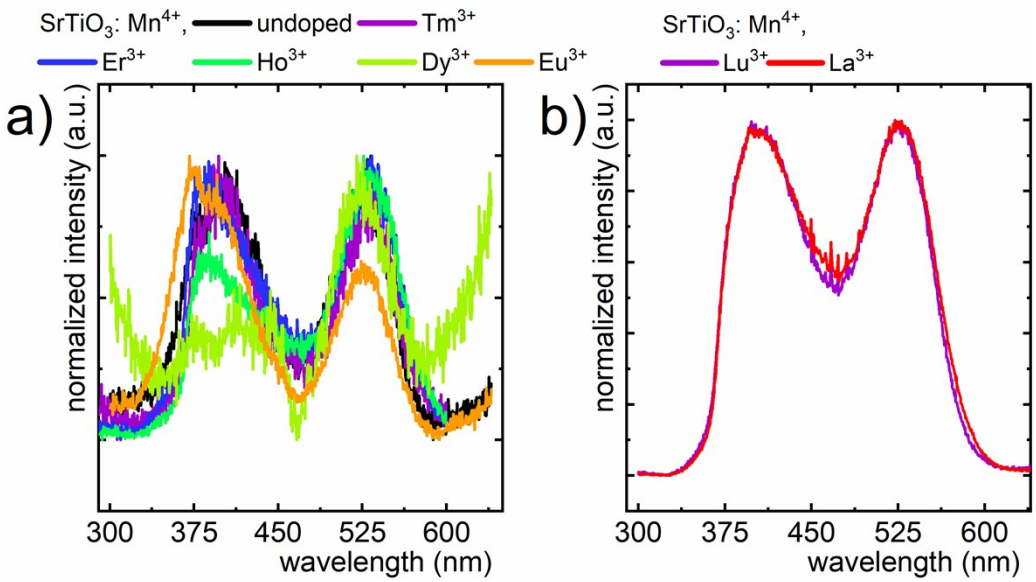

Figure S2. Excitation spectra of $SrTiO_3$:Mn^{4+}, Ln^{3+} with different optically active-a) and passive -b) Ln^{3+} ions measured at 123 K for emission of Mn^{4+} (λ_{em} = 725 nm).

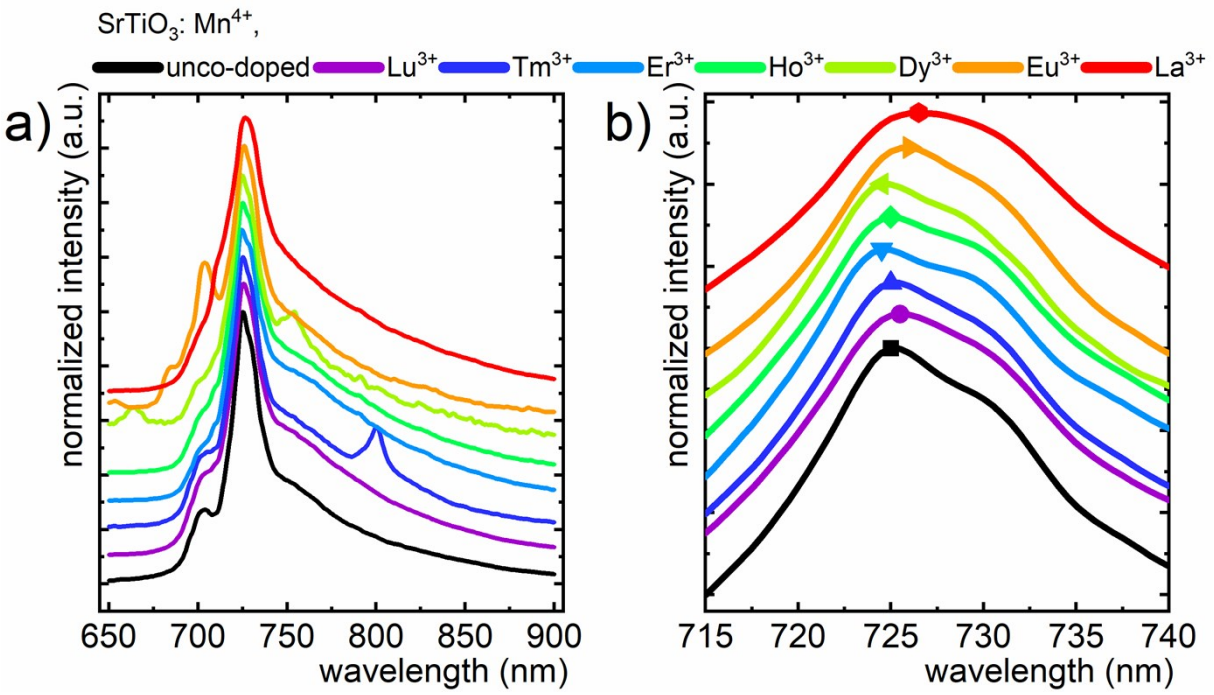

Figure S3. Emission spectra of $SrTiO_3$:Mn^{4+}, Ln^{3+} with different Ln^{3+} ions measured with λ_{exc} = 400 nm at 123 K – a) with the zoom of the same spectra in the 715-740 nm spectral range – b).

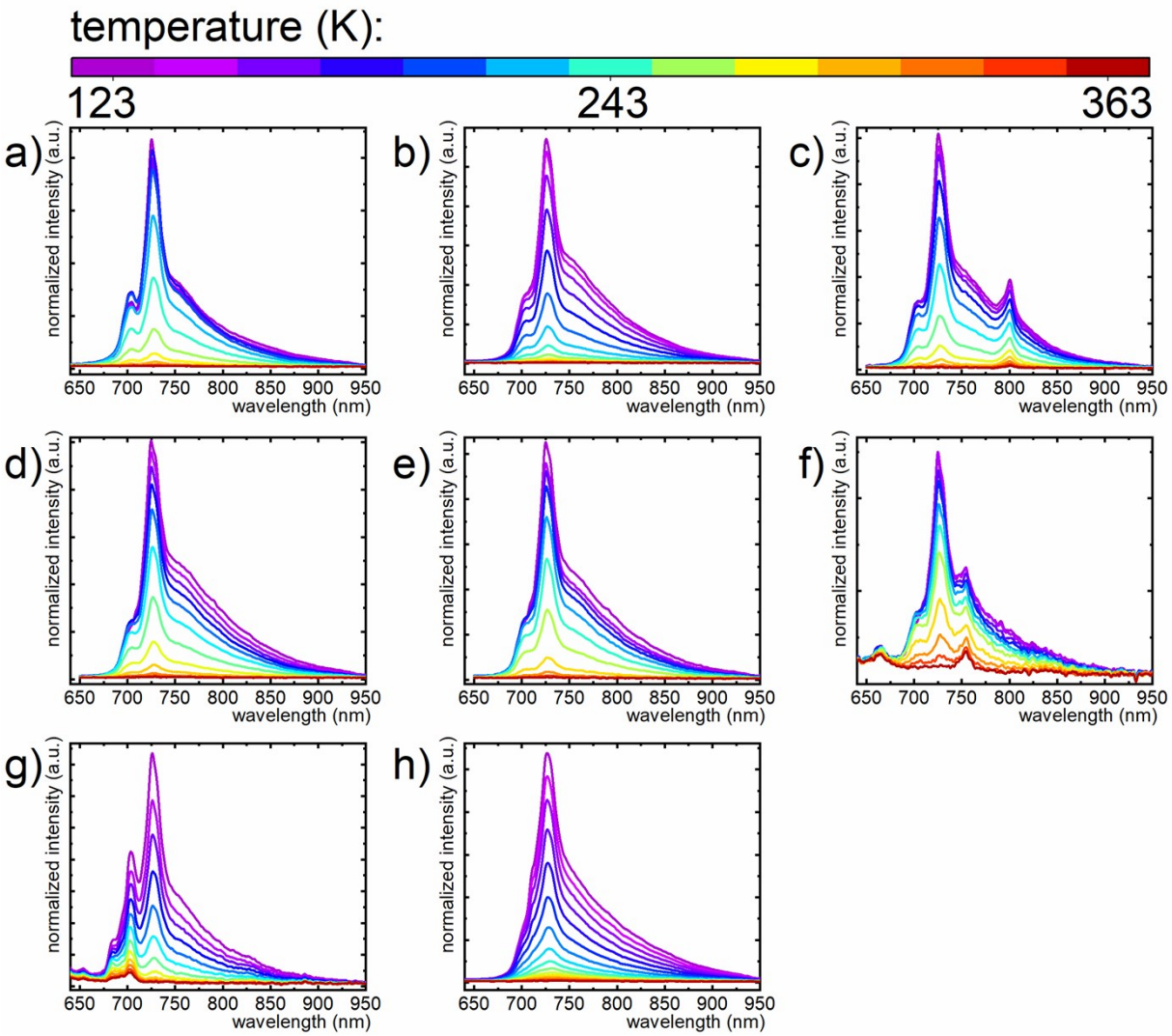

Figure S4. Thermal evolution of emission spectra excited by λ_{exc} = 400 nm for the $SrTiO_3$:0.1% Mn^{4+} – a) and $SrTiO_3$:0.1% Mn^{4+}, Ln^{3+}, where Ln^{3+} = Lu^{3+} – b), Tm^{3+} – c), Er^{3+} – d), Ho^{3+} – e), Dy^{3+} – f), Eu^{3+} – g), La^{3+} – h).

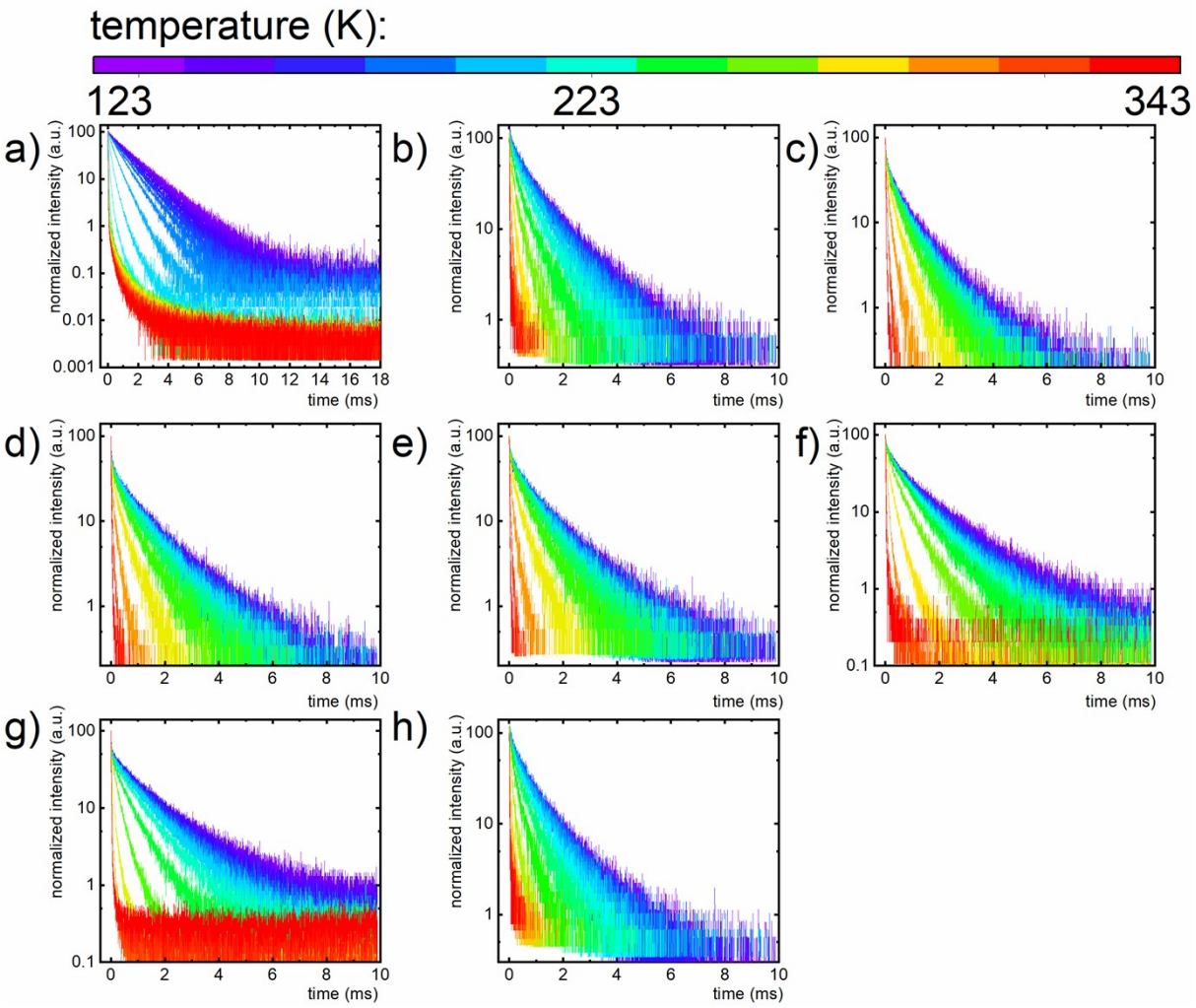

Figure S5. Thermal evolution of luminescent decays of ^2E excited state of Mn^{4+} for the $SrTiO_3$:0.1% Mn^{4+} – a) and $SrTiO_3$:0.1% Mn^{4+}, Ln^{3+}, where Ln^{3+} = Lu^{3+} – b), Tm^{3+} – c), Er^{3+} – d), Ho^{3+} – e), Dy^{3+} – f), Eu^{3+} – g), La^{3+} – h).

Table S2. The comparison of energy distances of Ln^{3+} excited states from ^2E of Mn^{4+} ions and thermometric parameters.

co-dopant ion	Eu^{3+}	Dy^{3+}	Er^{3+}	Ho^{3+}	Lu^{3+}	La^{3+}	Tm^{3+}
energy distance of excited state above ^2E (cm^{-1})	3436	7228	1591	1658	-	-	689
energy distance of excited state below ^2E (cm^{-1})	8144	560	11 07	299	-	-	940
mean energy distance of excited state from ^2E (cm^{-1})	5790	3894	1349	978.5	--	--	814.5
τ_{avr} at 123 K (ms)	0.90	0.86	0.78	0.71	0.71	0.61	0.54
local minimum value of S_A	2.5331	2.3892	1.9774	1.6879	2.066	~0.8894	~1.373

(μs K^{-1})							
temperature of $S_{A\ min}$ (K)	196.9	199.8	182.4	164.9	173.15	~131.4	~190.05
maximum value of S_A (μs K^{-1})	10.959	10.003	10.155	9.4355	7.5298	6.3693	7.1677
temperature of $S_{A\ max}$ (K)	263.5	265.2	254.7	251.9	249.15	248.9	261.9

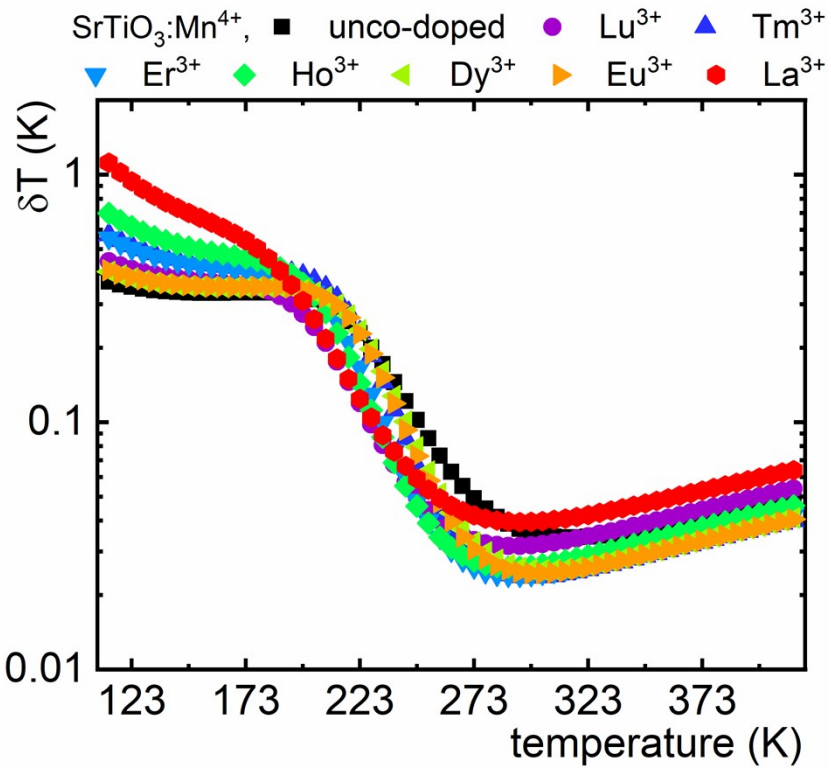

Figure S6. Thermal dependence of temperature estimation uncertainty for different Ln^{3+} in $SrTiO_3:Mn^{4+}$, Ln^{3+} samples.

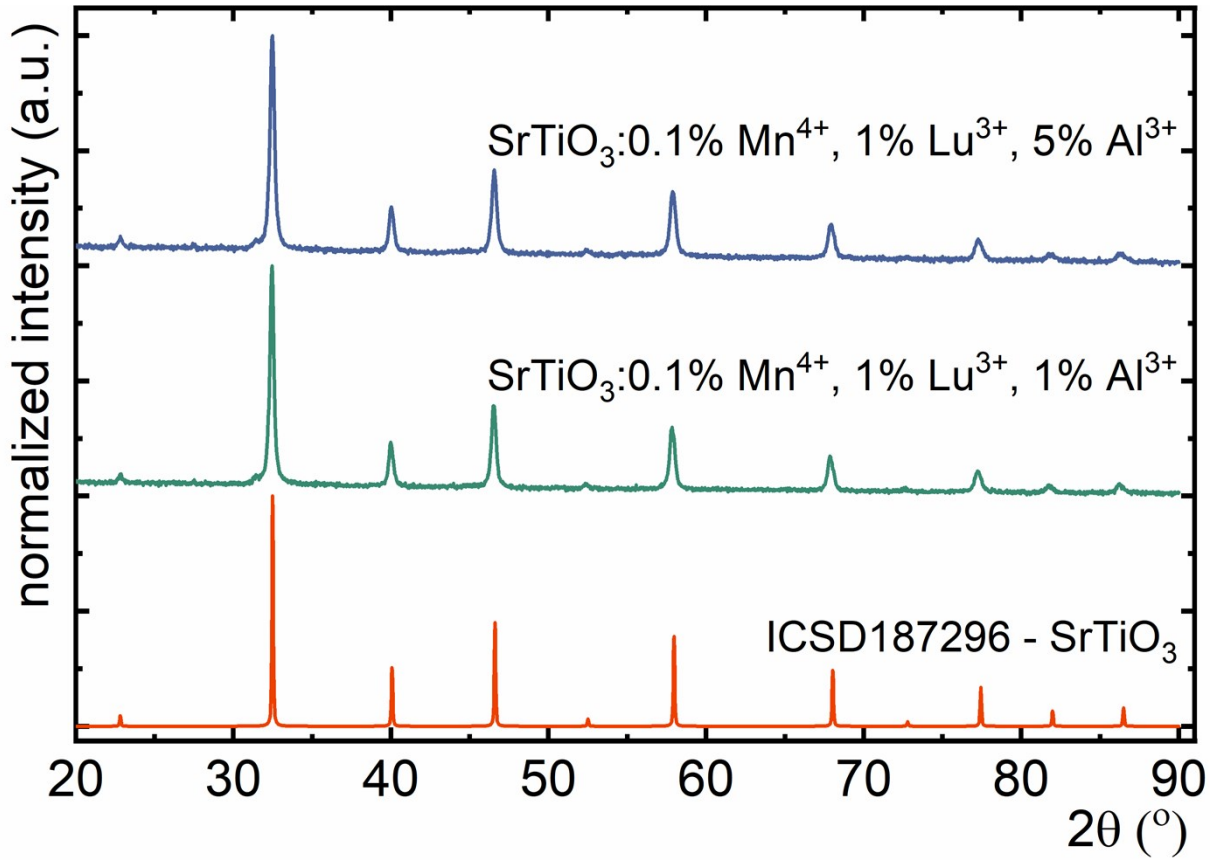

Figure S7. X-ray diffraction patterns of $SrTiO_3$:Mn^{4+}, Lu^{3+} co-doped with 1% and 5% of Al^{3+} ions.

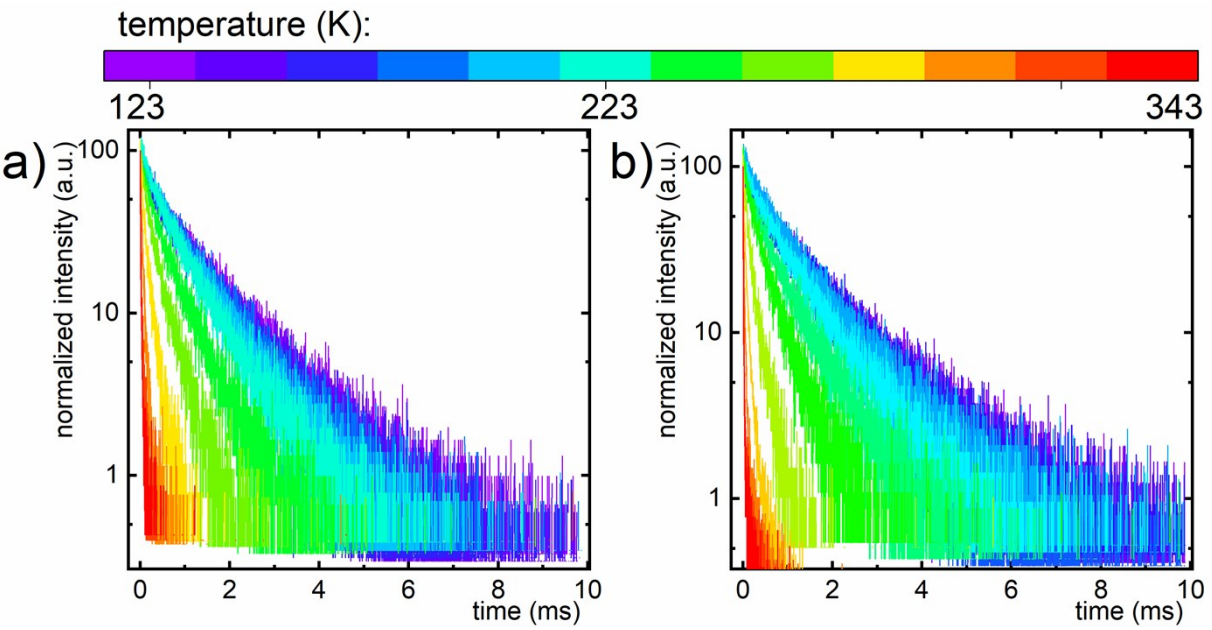

Figure S8. Thermal evolution of luminescent decays of ^2E excited state of Mn^{4+} for the $SrTiO_3$:0.1% Mn^{4+}, 1% Lu^{3+}, 1% Al^{3+} - a and $SrTiO_3$:0.1% Mn^{4+}, 1% Lu^{3+}, 5% Al^{3+} - b.