Supporting Information

Novel color-tunable Ce^{3+}/Ln^{3+} (Ln=Tb, Sm, Dy) co-doped borate phosphors with high energy transfer efficiency and excellent thermal stability

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Experimental Section

Synthesis

KSBO: Ce^{3+}/Ln^{3+} phosphors were synthesized by a high-temperature solid-state reaction with K_2CO_3 (99%., Aladdin), Sr_2CO_3 (99.9%., Aladdin), H_3BO_3 (99.99%., Aladdin), CeO_2 (99.99%, Aladdin), Tb_2O_3 (99.99%, Aladdin), Sm_2O_3 (99.99%, Aladdin) and Dy_2O_3 (99.99%, Aladdin) as raw materials. The above stating materials were weighed according to the stoichiometric ratio and then grounded in an agate mortar for 0.5h. The mixtures were grounded and sintered at 800 ^oC for 8 h in a muffle furnace. Finally, the as-prepared samples were cooled down to atmospheric temperature for further analysis.

PDMS films were synthesized from DOWSIL SYLGARD184, three phosphors: KSBO: 1%Ce^{3+}, 7%Tb^{3+}、KSBO: 1%Ce^{3+}, 1%Sm^{3+} and KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}, as well as curing agent.

XRD, Rietveld refinement and SEM

The XRD patterns were measured by DX-2700BH (Dandong HaoYuan Co. Ltd) with 30 mA

and 40 kV. CuKa radiation is used as excitation source with angle range between 10° and 80°. Program GSAS was used to calculate the crystal structure of KSBO. The elemental analysis and morphology were performed using a Hitachi S-4800 equipped with an energy-dispersive spectroscopy (EDS) detector.

Luminescence Spectra

An FSL 1000 fluorescence spectrophotometer was employed to examine the photoluminescence spectra and the fluorescence decay times. A 450 W xenon light source was equipped on a fluorescence spectrophotometer. The internal quantum efficiency values were measured using the integrated sphere on the same FLS1000 instrument. The temperature dependent spectra were measured by a self-built platform for in situ UV-Vis absorption and fluorescence measurement equipped with a 360 nm laser source under high pressure with a modified spectrophotometer (Ocean Optics, QE65 Pro).

Table. S1 Rietveld refinement results of KSBO.

Formula	KSBO
Crystal system	orthorhombic
Space group	*Ama2*
Cell parameters	a = 11.0403(66) Å,
	b = 11.9893(03) Å,
	c = 6.8834(24) Å
	$\alpha = \beta = \gamma = 90°$
	V = 911.13(33) Å^3
	Z = 4

Reliability factors	R_{wp} = 12.56%, R_p = 8.71%, χ^2 = 1.259

Table. S2 Selected interatomic bond distances of KSBO phosphors.

bond distance(Å)		bond distance(Å)		bond distance(Å)	
Sr1-O1	2.63499(7)	Sr2-O1	2.59450(5)	Sr3-O2	2.94821(5)
Sr1-O2	2.32249(5)	Sr2-O3	2.51834(4)	Sr3-O2	2.94821(5)
Sr1-O3	2.61677(5)	Sr2-O3	2.55372(4)	Sr3-O3	2.67487(4)
Sr1-O3	2.61677(5)	Sr2-O4	2.62297(5)	Sr3-O3	2.67487(4)
Sr1-O4	2.59845(5)	Sr2-O4	2.58049(5)	Sr3-O4	2.58090(6)
Sr1-O4	2.59845(5)	Sr2-O5	2.47218(5)	Sr3-O4	2.58090(6)
Sr1-O5	2.62592(6)	Sr2-O5	2.66135(4)	Sr3-O5	2.86604(5)
Sr1-O5	2.62592(6)	Sr2-O6	2.60007(6)	Sr3-O5	2.86604(5)
				Sr3-O6	2.64830(7)

Table. S3 CIE coordinates of KSBO: 1%Ce^{3+}, x%Tb^{3+} ($0.5 \leq x \leq 7$).

Formula	**Chromaticity coordinates**
KSBO: 1%Ce^{3+}, 0.5%Tb^{3+}	(0.1716, 0.0639)
KSBO: 1%Ce^{3+}, 1%Tb^{3+}	(0.1756, 0.0709)
KSBO: 1%Ce^{3+}, 3%Tb^{3+}	(0.1921, 0.1165)
KSBO: 1%Ce^{3+}, 5%Tb^{3+}	(0.2171, 0.1908)
KSBO: 1%Ce^{3+}, 7%Tb^{3+}	(0.2341, 0.2395)

Table. S4 CIE coordinates of KSBO: 1%Ce^{3+}, x%Sm^{3+} ($1 \leq x \leq 9$).

Formula	Chromaticity coordinates
KSBO: 1%Ce^{3+}, 1%Sm^{3+}	(0.2355, 0.0902)
KSBO: 1%Ce^{3+}, 3%Sm^{3+}	(0.261, 0.119)
KSBO: 1%Ce^{3+}, 5%Sm^{3+}	(0.2743, 0.1298)
KSBO: 1%Ce^{3+}, 7%Sm^{3+}	(0.2813, 0.1421)
KSBO: 1%Ce^{3+}, 9%Sm^{3+}	(0.2938, 0.1577)

Table. S5 CIE coordinates of KSBO: 0.5%Ce^{3+}, x%Dy^{3+} ($1 \leq x \leq 9$).

Formula	Chromaticity coordinates
KSBO: 0.5%Ce^{3+}, 1%Dy^{3+}	(0.2277, 0.1509)
KSBO: 0.5%Ce^{3+}, 3%Dy^{3+}	(0.2592, 0.2097)
KSBO: 0.5%Ce^{3+}, 5%Dy^{3+}	(0.2795, 0.2473)
KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}	(0.2842, 0.2557)
KSBO: 0.5%Ce^{3+}, 9%Dy^{3+}	(0.2882, 0.2639)

Table. S6 The fitting results and average lifetimes of PL decay curves of KSBO: 1%Ce^{3+}, *x*%Tb^{3+} ($0.5 \leq x \leq 7$) with 351 nm excitation and 417 nm emission.

Formula	τ_1(μs)	τ_2(μs)	τ (μs)
KSBO: 1%Ce^{3+}, 0.5%Tb^{3+}	27.85	41.19	38.39
KSBO: 1%Ce^{3+}, 1%Tb^{3+}	27.36	40.89	37.67
KSBO: 1%Ce^{3+}, 3%Tb^{3+}	22.80	38.62	36.68
KSBO: 1%Ce^{3+}, 5%Tb^{3+}	23.10	38.71	35.83
KSBO: 1%Ce^{3+}, 7%Tb^{3+}	20.19	37.80	35.21

Table. S7 The fitting results and average lifetimes of PL decay curves of KSBO: 1%Ce^{3+}, *x*%Sm^{3+} ($1 \leq x \leq 9$) with 351 nm excitation and 417 nm emission.

Formula	τ_1(μs)	τ_2(μs)	τ (μs)
KSBO: 1%Ce^{3+}, 1%Sm^{3+}	14.45	34.40	32.04
KSBO: 1%Ce^{3+}, 3%Sm^{3+}	10.72	30.30	27.18
KSBO: 1%Ce^{3+}, 5%Sm^{3+}	10.22	28.75	25.08
KSBO: 1%Ce^{3+}, 7%Sm^{3+}	9.71	27.96	23.37
KSBO: 1%Ce^{3+}, 9%Sm^{3+}	8.90	27.40	22.20

Table. S8 The fitting results and average lifetimes of PL decay curves of KSBO: 0.5%Ce^{3+}, x%Dy^{3+} ($1 \leq x \leq 9$) with 351 nm excitation and 417 nm emission.

Formula	τ_1(μs)	τ_2(μs)	τ (μs)
KSBO: 0.5%Ce^{3+}, 1%Dy^{3+}	21.33	36.63	34.46
KSBO: 0.5%Ce^{3+}, 3%Dy^{3+}	20.62	36.57	32.97
KSBO: 0.5%Ce^{3+}, 5%Dy^{3+}	16.86	34.31	31.15
KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}	14.66	33.12	30.15
KSBO: 0.5%Ce^{3+}, 9%Dy^{3+}	14.71	33.21	29.54

Table. S9 CIE coordinates of KSBO: 1%Ce^{3+}, 7%Tb^{3+}.

Temperature (℃)	Chromaticity coordinates
20	(0.2369, 0.2431)
50	(0.2367, 0.2434)
80	(0.2361, 0.2427)
110	(0.2361, 0.2422)
140	(0.2351, 0.2421)
170	(0.2362, 0.2438)
200	(0.2335, 0.2387)
230	(0.2355, 0.2428)

Table. S10 CIE coordinates of KSBO: 1%Ce^{3+}, 1%Sm^{3+}.

Temperature (℃)	Chromaticity coordinates
20	(0.2429, 0.1236)
50	(0.2410, 0.1250)
80	(0.2380, 0.1256)
110	(0.2356, 0.1285)
140	(0.2367, 0.1331)
170	(0.2352, 0.1353)
200	(0.2347, 0.1400)
230	(0.2343, 0.1443)

Table. S11 CIE coordinates of KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}.

Temperature (℃)	Chromaticity coordinates
20	(0.2814, 0.2644)
50	(0.2811, 0.2649)
80	(0.2829, 0.2643)
110	(0.2811, 0.2661)
140	(0.2810, 0.2670)
170	(0.2806, 0.2668)
200	(0.2801, 0.2669)
230	(0.2799, 0.2669)

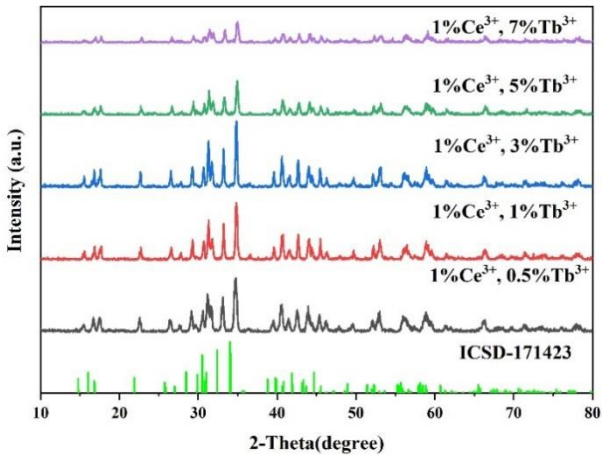

Fig. S1 XRD diffraction patterns of KSBO: 1%Ce^{3+}, x%Tb^{3+} ($0.5 \leq x \leq 7$).

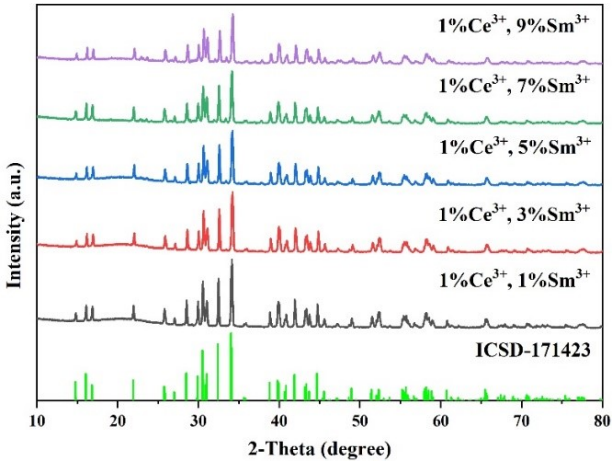

Fig. S2 XRD diffraction patterns of KSBO: 1%Ce^{3+}, x%Sm^{3+} ($1 \leq x \leq 9$).

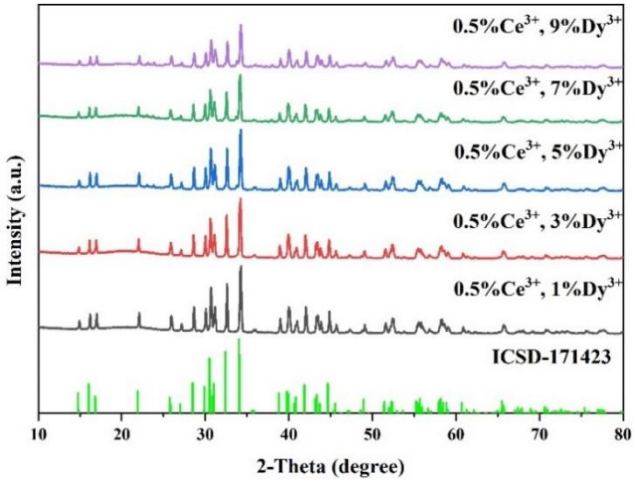

Fig. S3 XRD diffraction patterns of KSBO: 0.5%Ce^{3+}, x%Dy^{3+} ($1 \leq x \leq 9$).

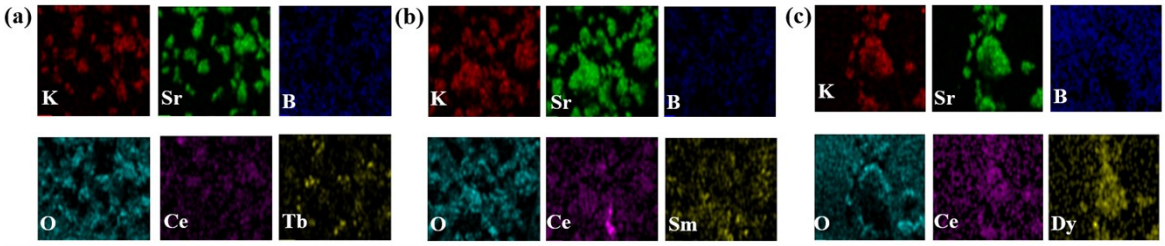

Fig. S4 Element mapping images of (a) KSBO: 1%Ce^{3+}, 7%Tb^{3+}, (b) KSBO: 1%Ce^{3+}, 1%Sm^{3+} and (c) KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}.

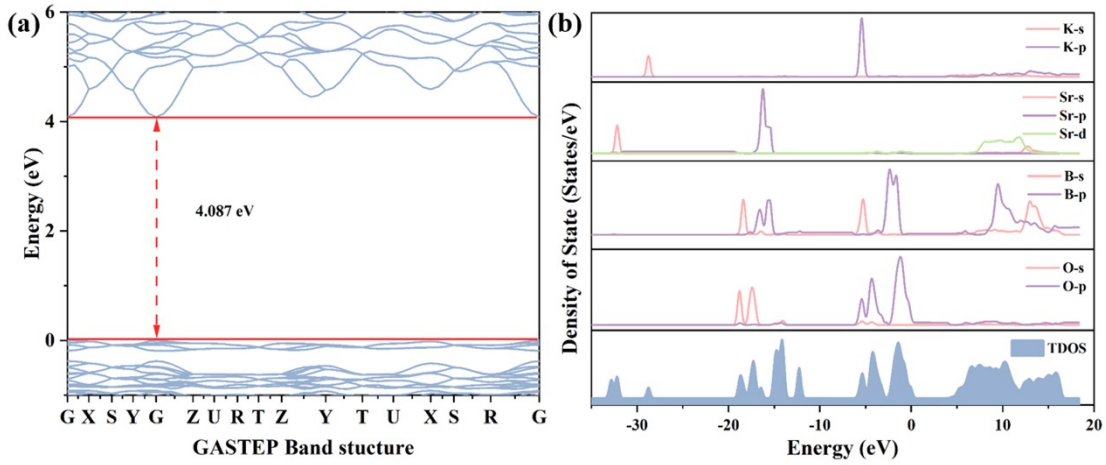

Fig. S5 (a) Band structure of KSBO. (b) Total and partial density of states of the KSBO.

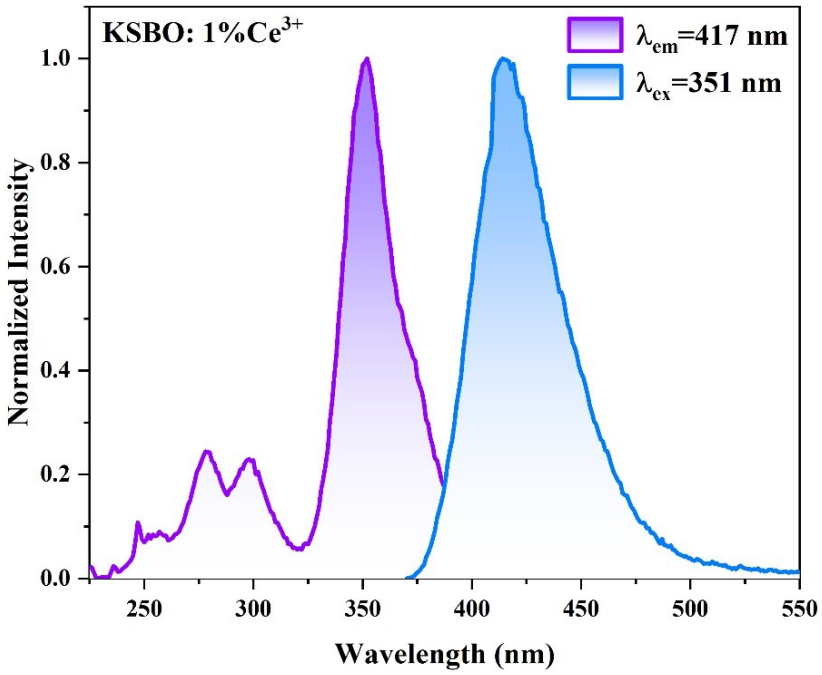

Fig. S6 Excitation spectrum and emission spectrum of KSBO: 1%Ce^{3+}.

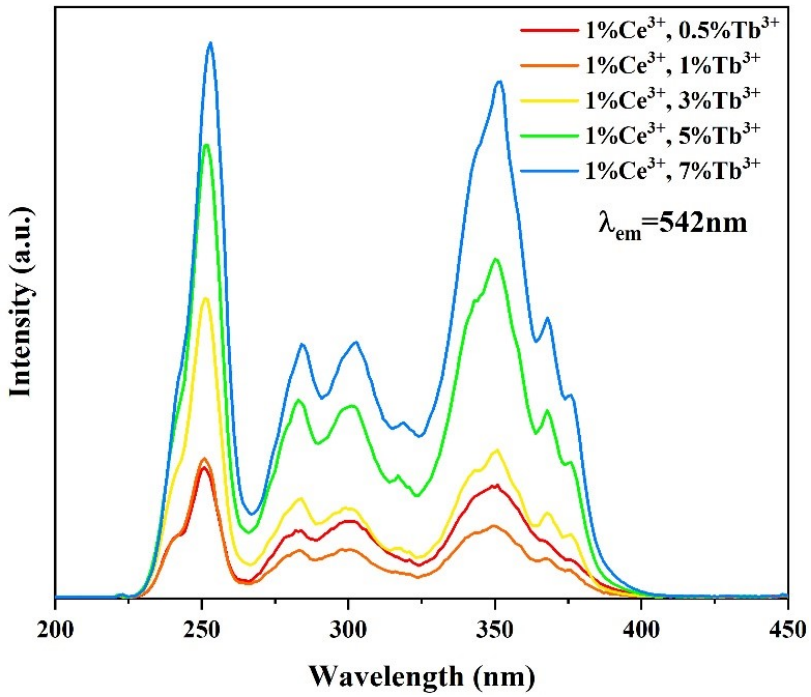

Fig. S7 Excitation spectra of KSBO: 1%Ce^{3+}, x%Tb^{3+} ($0.5 \leq x \leq 7$).

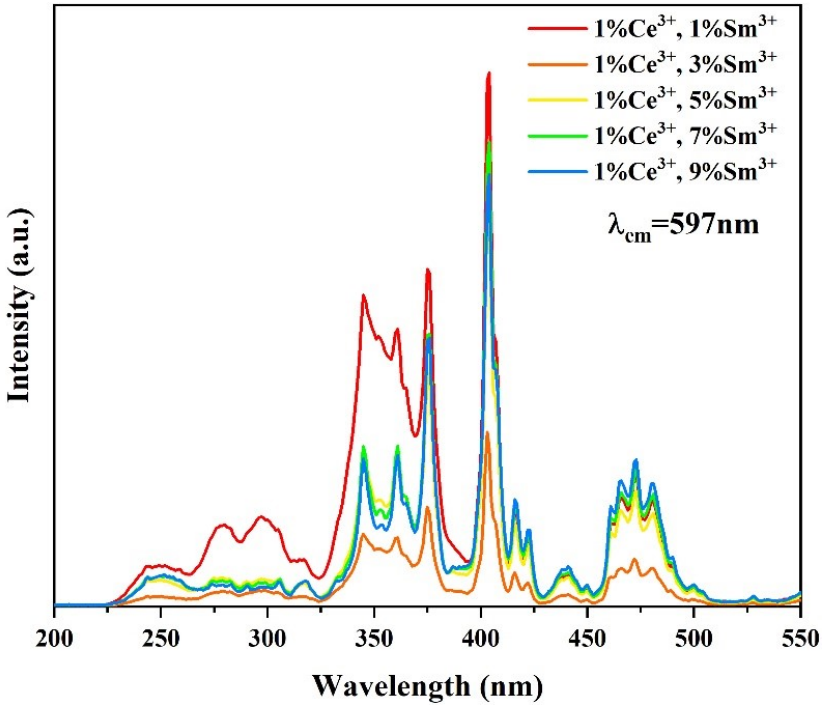

Fig. S8 Excitation spectra of KSBO: 1%Ce^{3+}, x%Sm^{3+} ($1 \leq x \leq 9$).

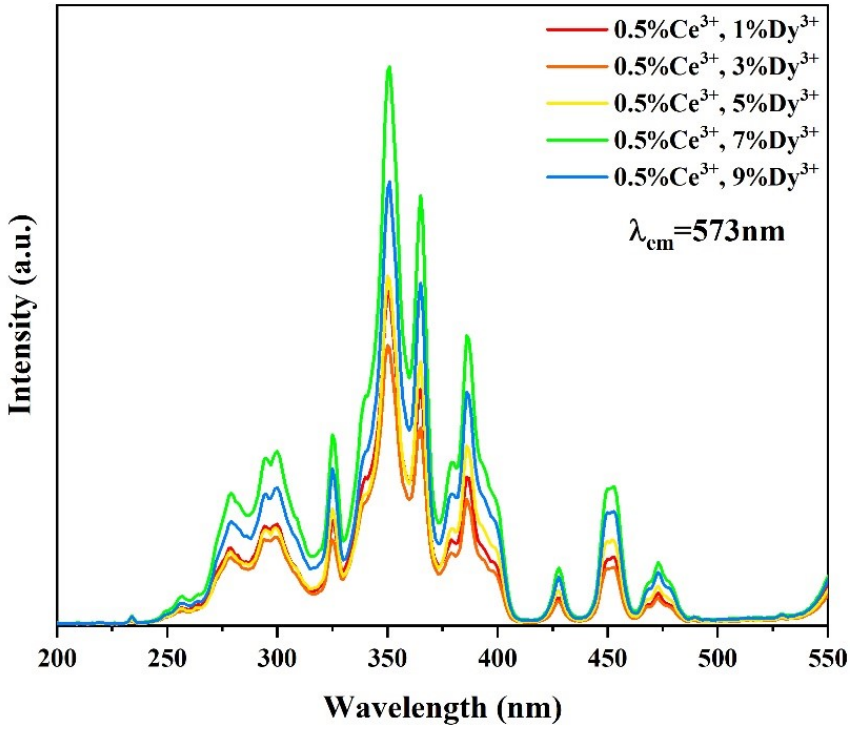

Fig. S9 Excitation spectra of KSBO: 0.5%Ce^{3+}, x%Dy^{3+} ($1 \leq x \leq 9$).

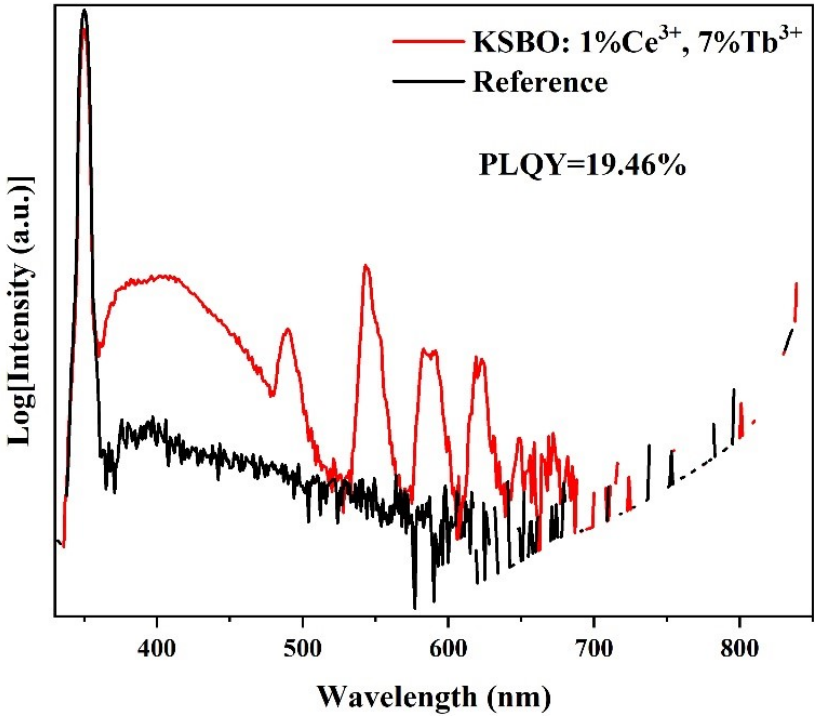

Fig. S10 PLQY of KSBO: 1%Ce^{3+}, 7%Tb^{3+}.

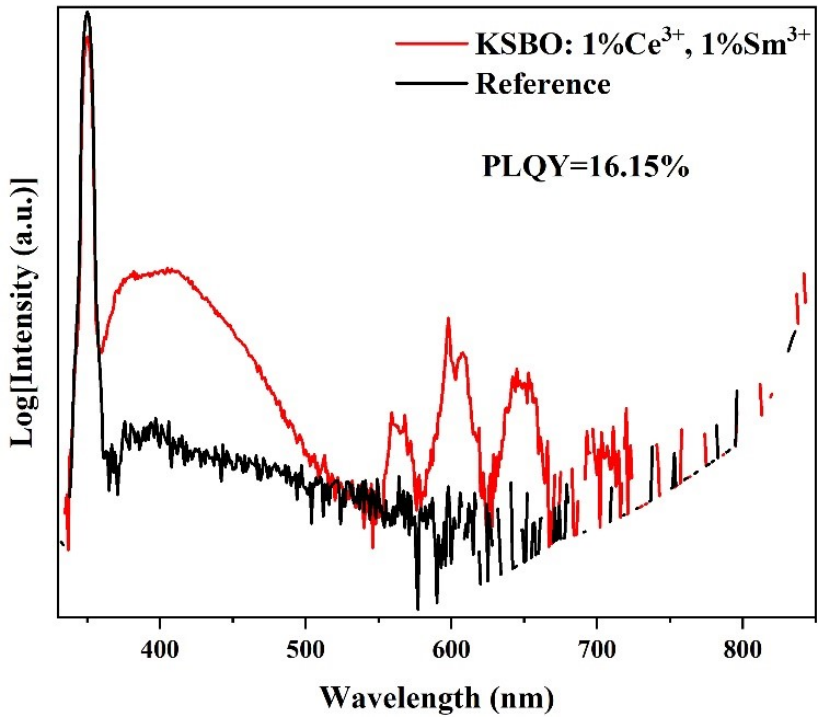

Fig. S11 PLQY of KSBO: 1%Ce^{3+}, 1%Sm^{3+}.

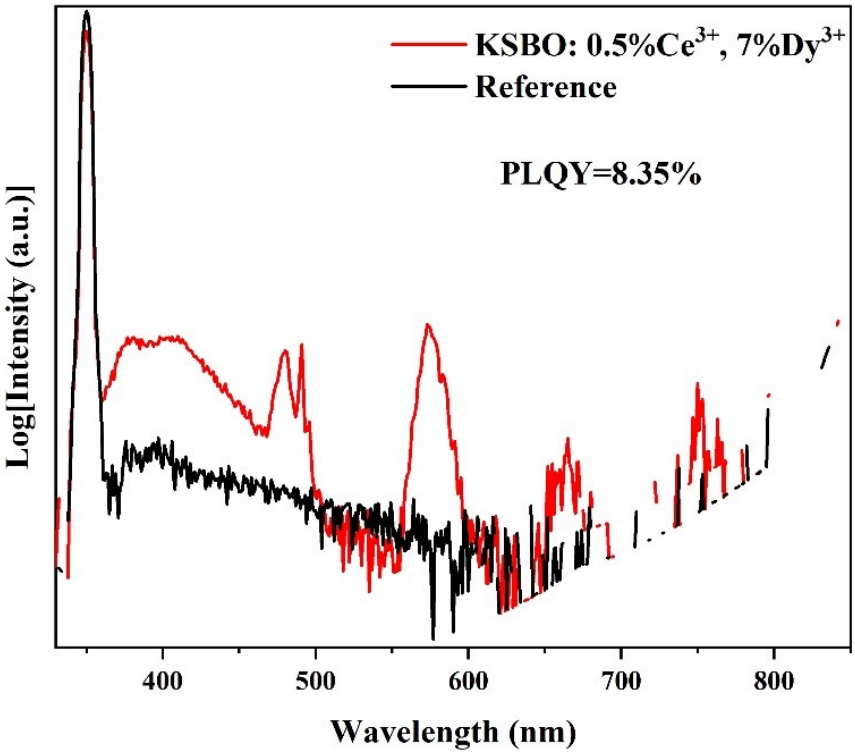

Fig. S12 PLQY of KSBO: 0.5%Ce^{3+}, 7%Dy^{3+}.

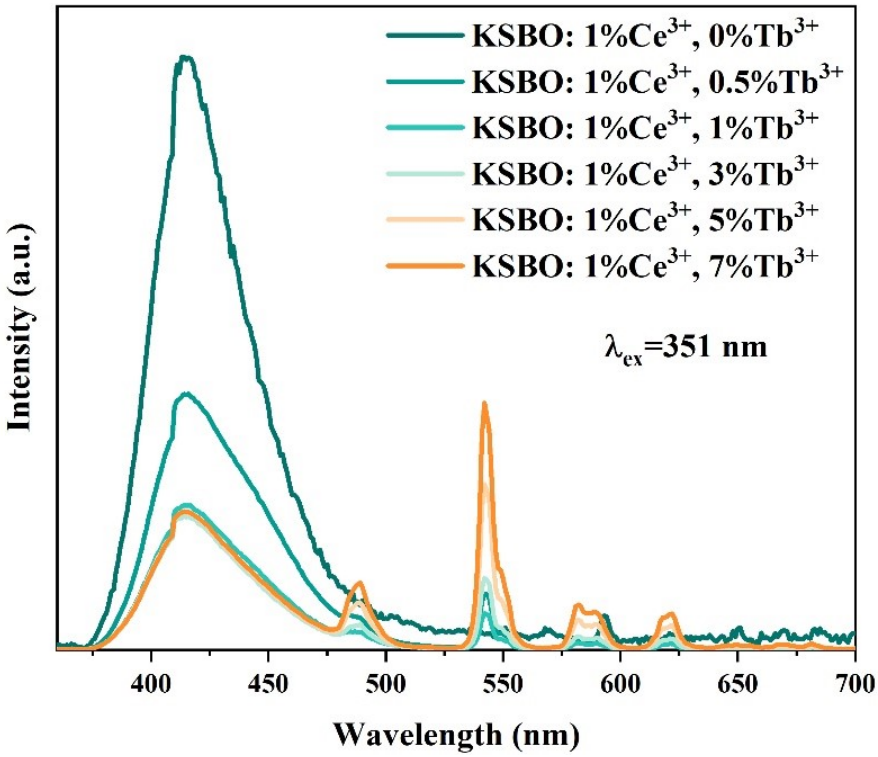

Fig. S13 Emission spectra of KSBO: 1%Ce^{3+}, x%Tb^{3+} ($0 \leq x \leq 7$).

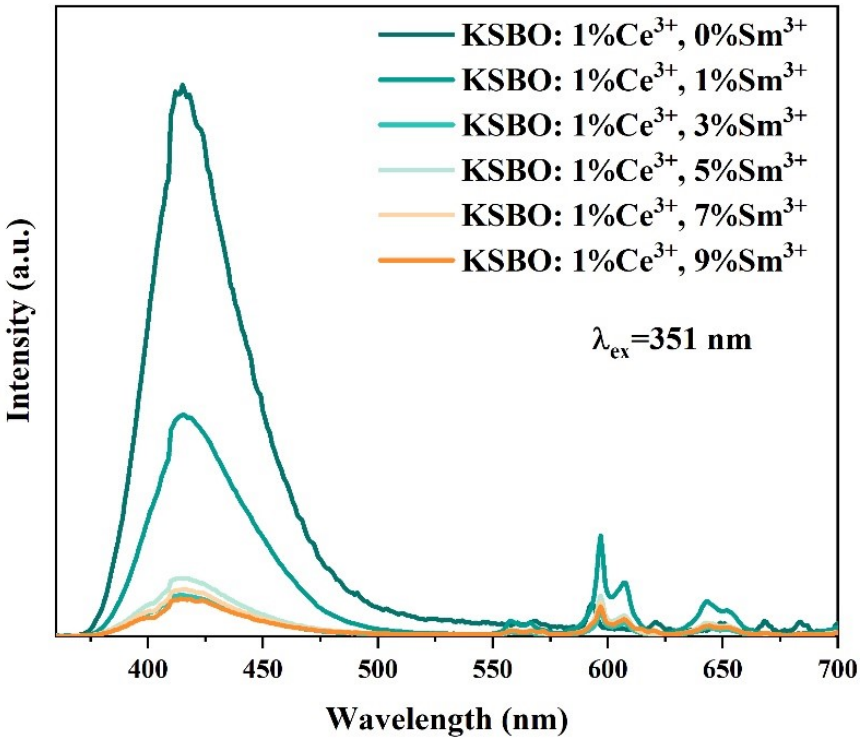

Fig. S14 Emission spectra of KSBO: 1%Ce^{3+}, x%Sm^{3+} ($0 \leq x \leq 9$).

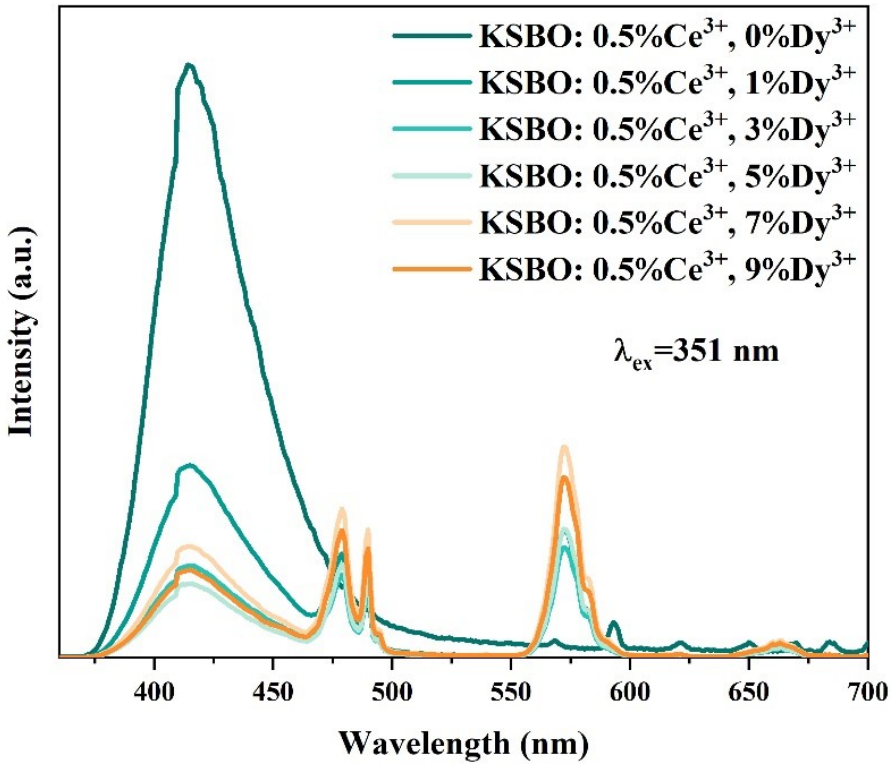

Fig. S15 Emission spectra of KSBO: 0.5%Ce^{3+}, x%Dy^{3+} ($0 \leq x \leq 9$).