materials

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Supplementary Materials

Optical properties investigation of upconverting $K_2Gd(PO_4)(WO_4)$:20%Yb^{3+},Tm^{3+} phosphors

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Table S1. Spectrometer settings for measuring reflection spectra of KGPW:20%Yb^{3+},Tm^{3+} phosphors.

KGPW:20%Yb^{3+},Tm^{3+}	
Parameter	
EmBW	0.15 nm
ExBW	4.00 nm
Step	0.50 nm
Integration time	0.200 s
Range	250 – 800 nm
Repeats	3

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Table S2. Spectrometer settings for measuring excitation spectra of KGPW:20%Yb^{3+},Tm^{3+} phosphors.

KGPW:20%Yb^{3+},Tm^{3+}		
Excitation scan	**Parameter**	
λ_{em} = 450 nm	EmBW	1.60 nm
	ExBW	0.50 nm
	Dwell	0.200 s
	Step	0.50 nm

Table S3. Spectrometer settings for measuring DC emission spectra of KGPW:20%Yb^{3+},Tm^{3+} phosphors.

KGPW:20%Yb^{3+},Tm^{3+}		
Emission scan	**Parameter**	
λ_{ex} = 360 nm	EmBW	0.50 nm
	ExBW	1.60 nm
	Dwell	0.200 s
	Step	0.50 nm

Table S4. Spectrometer settings for measuring UC emission spectra of KGPW:20%Yb^{3+},Tm^{3+} phosphors.

KGPW:20%Yb^{3+},Tm^{3+}		
Emission scan	**Parameter**	
λ_{ex} = 980 nm	EmBW	0.06 nm
	ExBW	N/A
	Dwell	0.200 s
	Step	0.50 nm

Table S5. Lattice parameters of KGPW, KGPW:5%Tm^{3+}, KGPW:20%Yb^{3+}, and KGPW:20%Yb^{3+},5%Ho^{3+} samples derived from Rietveld refinement analysis.

Sample	***a*, Å**	***b*, Å**	***c*, Å**	***V*, Å^3**	**Ref.**
$K_2Ho(PO_4)(WO_4)$	6.8820	12.1485	19.6950	1646.6	**[1]**
$K_2Gd(PO_4)(WO_4)$	6.94294	12.24594	19.68550	1673.7	This work
$K_2Gd(PO_4)(WO_4)$:5%Tm^{3+}	6.94232	12.24028	19.69242	1673.4	This work
$K_2Gd(PO_4)(WO_4)$:20%Yb^{3+}	6.92142	12.20985	19.67467	1662.7	This work
$K_2Gd(PO_4)(WO_4)$:20%Yb^{3+}, 5%Tm^{3+}	6.92048	12.20600	19.67702	1662.1	This work

Table S6. Color coordinates (CIE 1931 color space) of KGPW:Tm^{3+} and KGPW:20%Yb^{3+},Tm^{3+} as a function of Tm^{3+} concentration and excitation wavelength.

Tm^{3+} (%)	**KGPW:Tm^{3+}**		**KGPW:20%Yb^{3+},Tm^{3+}**			
	λ_{ex} = 360 nm		**λ_{ex} = 360 nm**		**λ_{ex} = 980 nm**	
	x	**y**	**x**	**y**	**x**	**y**
0.5	0.15762	0.02803	0.15797	0.03672	0.14463	0.09657
1	0.15763	0.02889	0.15772	0.02931	0.16312	0.10567
2	0.15772	0.02840	0.15738	0.02821	0.14411	0.09332
5	0.15735	0.02924	0.15709	0.02718	0.14628	0.09301

Table S7. UC PL rise time and lifetime values of KGPW:Tm^{3+} and KGPW:20%Yb^{3+},Tm^{3+} phosphors as a function of Tm^{3+} concentration, emission wavelength, and excitation wavelength.

	Rise time (μs)	**Std. dev. (μs)**	**Lifetime τ_{eff} (μs)**	**Std. dev. (μs)**
Tm^{3+}(%)	**λ_{ex} = 360 nm λ_{em} = 450 nm**			
	KGPW:Tm^{3+}			
0.5	-	-	24	1
1	-	-	34	1
2	-	-	23	1
5	-	-	20	1
Tm^{3+}(%)	**λ_{ex} = 360 nm λ_{em} = 450 nm**			
	KGPW:20%Yb^{3+},Tm^{3+}			
0.5	-	-	22	1
1	-	-	22	1
2	-	-	21	1
5	-	-	19	1
Tm^{3+}(%)	**λ_{ex} = 980 nm λ_{em} = 478 nm**			
	KGPW:20%Yb^{3+},Tm^{3+}			
0.5	73	8	201	5
1	68	8	159	2
2	63	7	138	2
5	38	3	107	1
Tm^{3+}(%)	**λ_{ex} = 980 nm λ_{em} = 800 nm**			
	KGPW:20%Yb^{3+},Tm^{3+}			
0.5	36	2	267	3
1	52	6	204	3
2	56	7	158	2
5	39	2	101	1

Table S8. The calculated PL lifetime values (λ_{ex} = 980 nm, λ_{em} = 1050 nm) of Yb^{3+} emission in KGPW:20%Yb^{3+},Tm^{3+}, and Yb^{3+} → Tm^{3+} energy transfer efficiency (η_{tr}) as a function of Tm^{3+} concentration.

	Lifetime τ_{eff} (μs)	**Std. dev. (μs)**	**η_{tr} (%)**
Tm^{3+}(%)	**KGPW:20%Yb^{3+},Tm^{3+}**		
0	1312	24	-
0.5	738	5	44
1	544	4	59
2	457	4	65
5	416	4	68

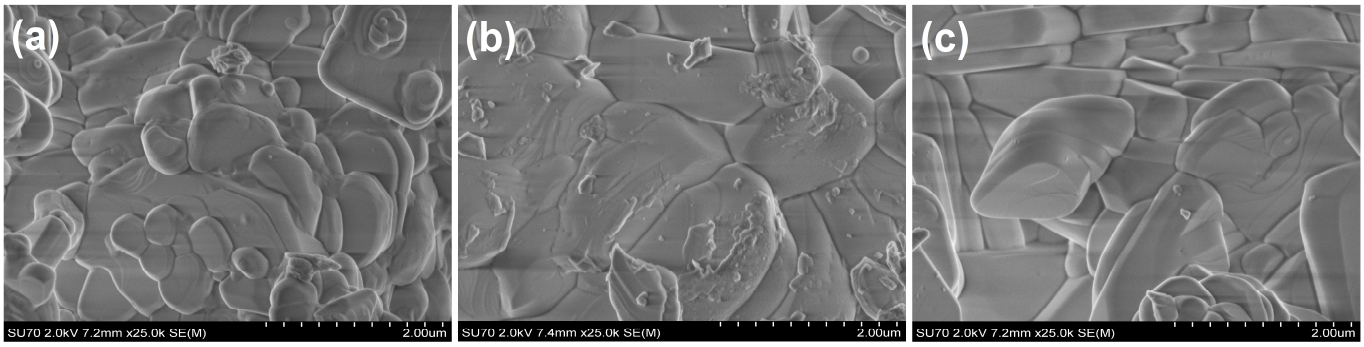

Figure S1. SEM images of (**a**) KGPW:5%Yb^{3+},(**b**) KGPW:20%Yb^{3+}, and (**c**) KGPW:20%Yb^{3+},5%Tm^{3+}.

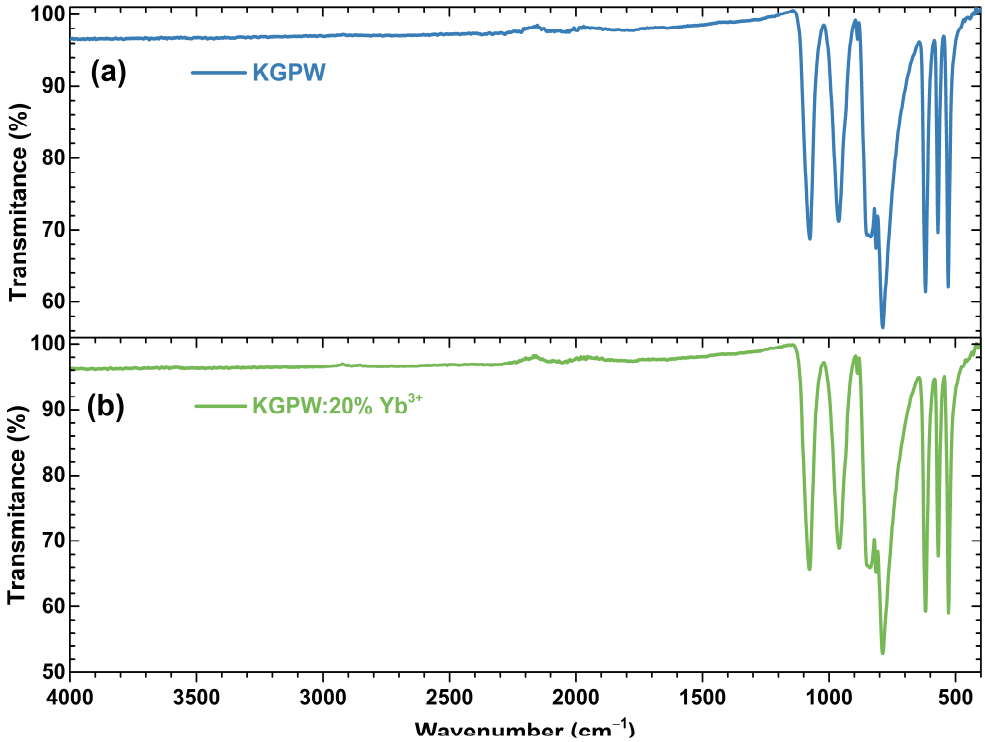

Figure S2. IR spectra of (**a**) undoped KGPW and (**b**) KGPW:20%Yb^{3+}.

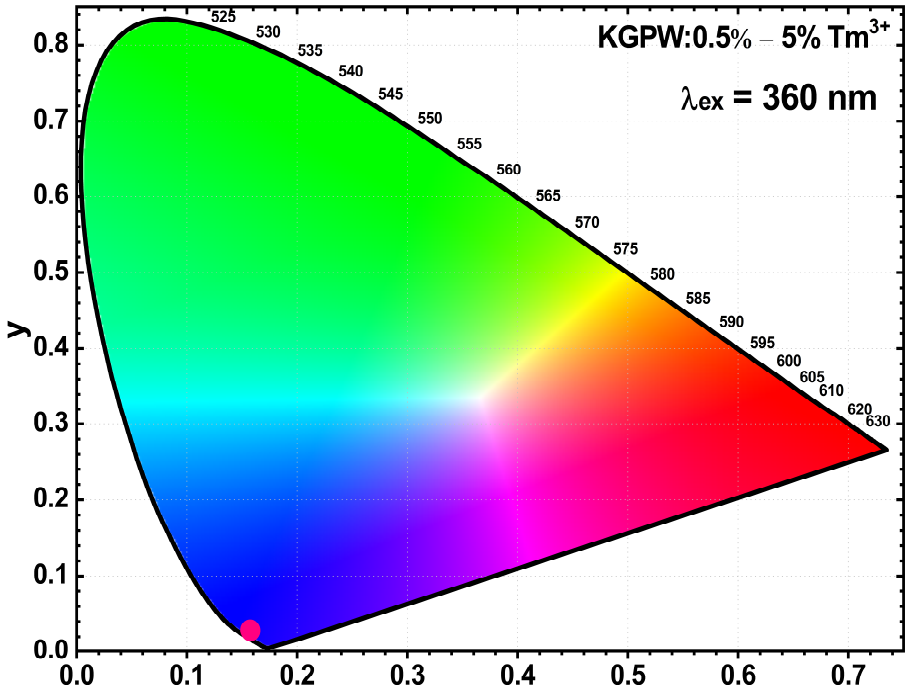

Figure S3. CIE 1931 color space diagram and color coordinates of KGPW:Tm^{3+} as a function of Tm^{3+} concentration under 360 nm excitation.