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Supplementary information

Synthesis and Luminescence Properties of Green to Red Color Tunable Upconverting $K_2Gd(PO_4)(WO_4)$:Yb^{3+},Tb^{3+},Eu^{3+} Phosphors

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Table S1. Spectrometer settings for measuring reflection spectra of KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors.

KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{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

Table S2. Spectrometer settings for measuring excitation spectra of KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+}phosphors.

KGPW:10% Yb^{3+} 20% Tb^{3+}x% Eu^{3+}		
Excitation scan	**Parameter**	
λ_{em} = 614 nm	EmBW	0.50 nm
	ExBW	0.40 nm
	Dwell	0.200 s
	Step	0.50 nm

Table S3. Spectrometer settings for measuring down-conversion emission spectra of KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors.

KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+}		
Emission scan	**Parameter**	
λ_{ex} = 340 nm	EmBW	0.50 nm
	ExBW	2.30 nm
	Dwell	0.200 s
	Step	0.50 nm

Table S4. Spectrometer settings for measuring UC emission spectra of KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors.

KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+}		
Emission scan	**Parameter**	
λ_{ex} = 980 nm	EmBW	0.20 nm
	ExBW	0.02 nm
	Dwell	0.200 s
	Step	0.50 nm

Table S5. Lattice parameters of KGPW, KGPW:10%Yb^{3+}, KGPW:20%Tb^{3+}, KGPW:20%Eu^{3+}, and KGPW:10%Yb^{3+},20%Tb^{3+},20%Eu^{3+} samples derived from Rietveld refinement analysis.

Sample	***a*, Å**	***b*, Å**	***c*, Å**	***V*, Å^3**
KGPW	6.94294	12.24594	19.68550	1673.7
KGPW:10%Yb^{3+}	6.93468	12.22874	19.68747	1669.5
KGPW:20%Tb^{3+}	6.94003	12.23615	19.69107	1672.1
KGPW:20%Eu^{3+}	6.95011	12.25235	19.69756	1677.3
KGPW:10%Yb^{3+},20%Tb^{3+},20%Eu^{3+}	6.93084	12.22727	19.68238	1668.0

Table S6. The calculated effective PL lifetime values of KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors as a function of Eu^{3+} concentration (λ_{ex} = 340 nm, λ_{em} = 542 nm).

	Lifetime τ_{eff} (μs)	**Std. dev. (μs)**
Eu^{3+} (%)	**KGPW:20%Tb^{3+},Eu^{3+}**	
0	2286	2
1	2071	12
2.5	1905	7
5	1764	4
10	1696	5
20	1486	7
Eu^{3+} (%)	**KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+}**	
0	2236	2
1	1953	7
2.5	1950	7
5	1798	5
10	1727	6
20	1565	6

Table S7. The calculated effective PL lifetime values of KGPW:20%Tb^{3+},Eu^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors as a function of Eu^{3+} concentration (λ_{ex} = 340 nm, λ_{em} = 614 nm).

	Lifetime τ_{eff} (μs)	**Std. dev. (μs)**
Eu^{3+} (%)	**KGPW:20%Tb^{3+},Eu^{3+}**	
1	2712	3
2.5	2631	3
5	2592	3
10	2538	3
20	2511	2
Eu^{3+} (%)	**KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+}**	
1	2550	3
2.5	2506	3
5	2409	3
10	2263	3
20	2085	4

Table S8. The UC PL rise time and UC PL lifetime values of Tb^{3+} in KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors as a function of Eu^{3+} concentration (λ_{ex} = 980 nm, λ_{em} = 542 nm).

Eu^{3+} (%)	Rise time (μs)	Std. dev. (μs)	Lifetime τ_{eff} (μs)	Std. dev. (μs)
0	284	7	2055	3
1	218	3	1850	2
2.5	197	3	1801	2
5	180	4	1752	113
10	131	4	1612	47
20	113	10	1345	15

Table S9. The UC PL rise time and UC PL lifetime values of Eu^{3+} in KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} phosphors as a function of Eu^{3+} concentration (λ_{ex} = 980 nm, λ_{em} = 704 nm).

Eu^{3+} (%)	Rise time (μs)	Std. dev. (μs)	Lifetime τ_{eff} (μs)	Std. dev. (μs)
1	780	80	2414	3
2.5	671	58	2328	3
5	544	36	2214	3
10	433	26	2042	3
20	334	18	1765	3

Table S10. The PL lifetime values of Yb^{3+} in KGPW (λ_{ex} = 980 nm, λ_{em} = 1050 nm).

	Lifetime τ_{eff} (s)	Std. dev. (s)
KGPW:10%Yb^{3+},20%Tb^{3+}		
0%Eu^{3+}	1048	2
20%Eu^{3+}	924	1
KGPW:10%Yb^{3+}		
	1066	2

Table S11. Color coordinates (CIE 1931 color space) of the synthesized phosphors as a function of Eu^{3+} concentration under 340 nm and 980 nm excitation.

Eu^{3+}	**KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} λ_{ex} = 340 nm**	
(%)	**x**	**y**
1	0.40838	0.51417
2.5	0.43061	0.50295
5	0.47638	0.46792
10	0.5399	0.41674
20	0.59243	0.37876
Eu^{3+}	**KGPW:20%Tb^{3+},Eu^{3+} (λ_{ex} = 340 nm)**	
(%)	**x**	**y**
0	0.33596	0.57641
1	0.39017	0.53524
2.5	0.43543	0.49621
5	0.48339	0.45336
10	0.54806	0.40598
20	0.60062	0.37416
Eu^{3+}	**KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} (λ_{ex} = 980 nm)**	
(%)	**x**	**y**
0	0.30292	0.53827
1	0.37728	0.48815
2.5	0.39024	0.47583
5	0.44071	0.44732
10	0.50494	0.40587
20	0.55178	0.38397

Table S12. Color coordinates (CIE 1931 color space) of KGPW:10%Yb^{3+},20%Tb^{3+},5%Eu^{3+} sample as a function of temperature (λ_{ex} = 980 nm).

T (K)	KGPW:10%Yb^{3+},20%Tb^{3+},5% Eu^{3+}	
	CIE 1931	
	x	y
77	0.40203	0.48822
100	0.40859	0.49563
150	0.40933	0.50203
200	0.40744	0.50356
250	0.4062	0.50326
300	0.40511	0.50227
350	0.40555	0.50006
400	0.40547	0.49852
450	0.40608	0.49672
500	0.40632	0.49527

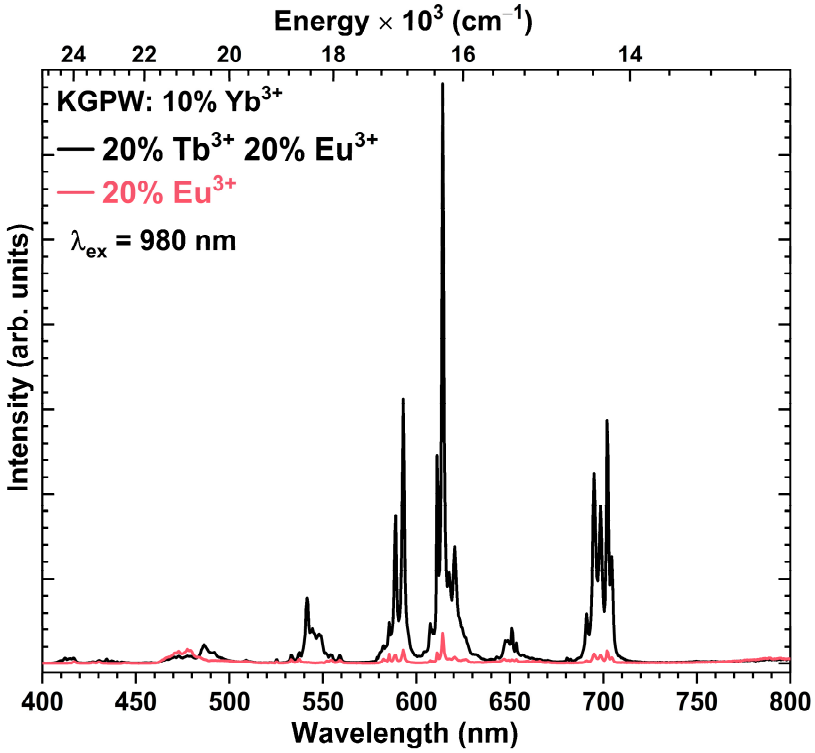


Figure S1. Emission spectra of KGPW:10%Yb^{3+},20%Tb^{3+},20%Eu^{3+} and KGPW:10%Yb^{3+},20%Eu^{3+} under 980 nm laser excitation.

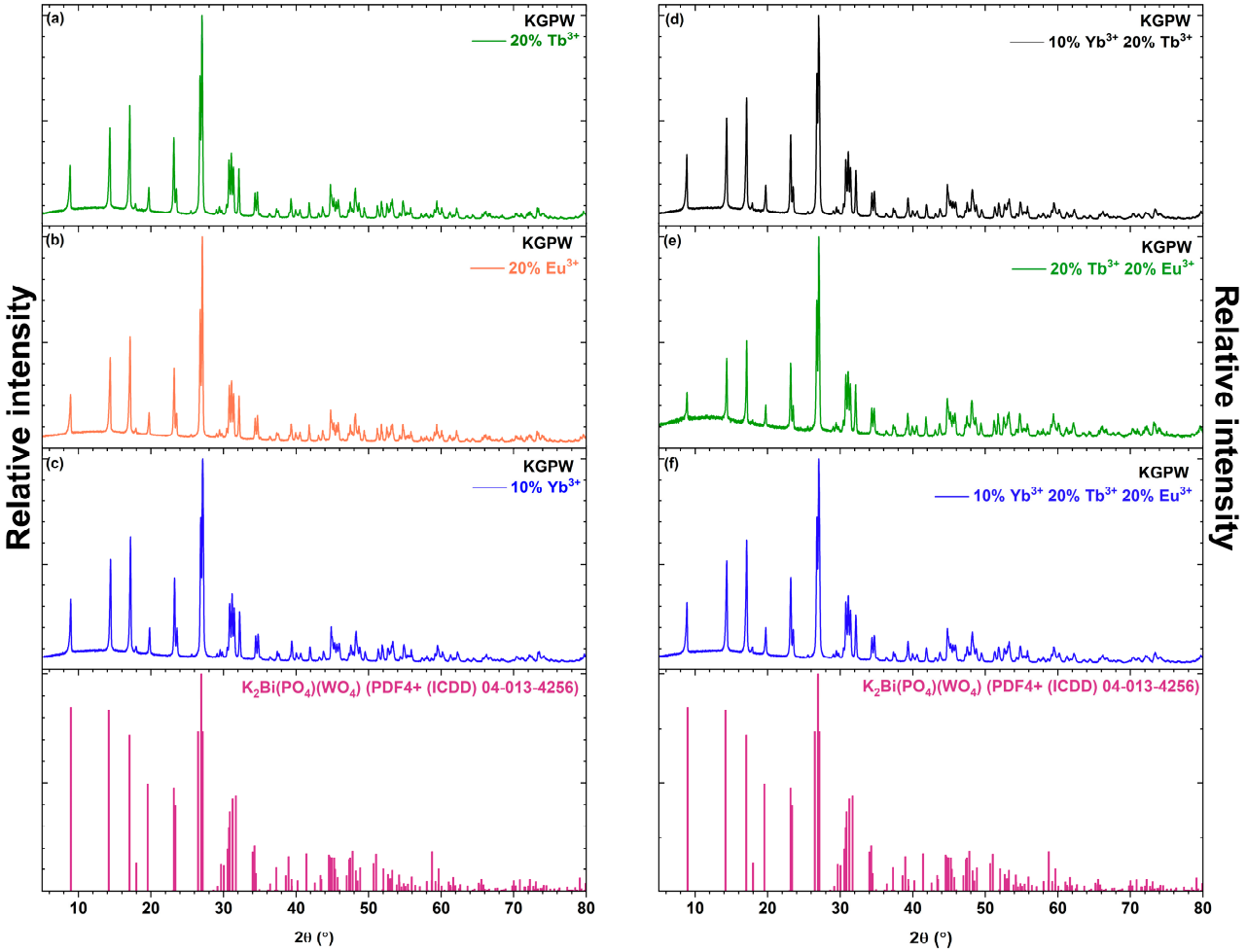


Figure S2. XRD patterns of KGPW doped with 20% Tb^{3+} (a), 20% Eu^{3+} (b), 10% Yb^{3+} (c), co-doped with 10% Yb^{3+} and 20% Tb^{3+} (d), 20% Tb^{3+} and 20% Eu^{3+} (e), and 10% Yb^{3+}, 20% Tb^{3+}, 20% Eu^{3+} (f). The reference pattern of $K_2Bi(PO_4)(WO_4)$ is given for comparison (PDF4+ 04-013-4256).

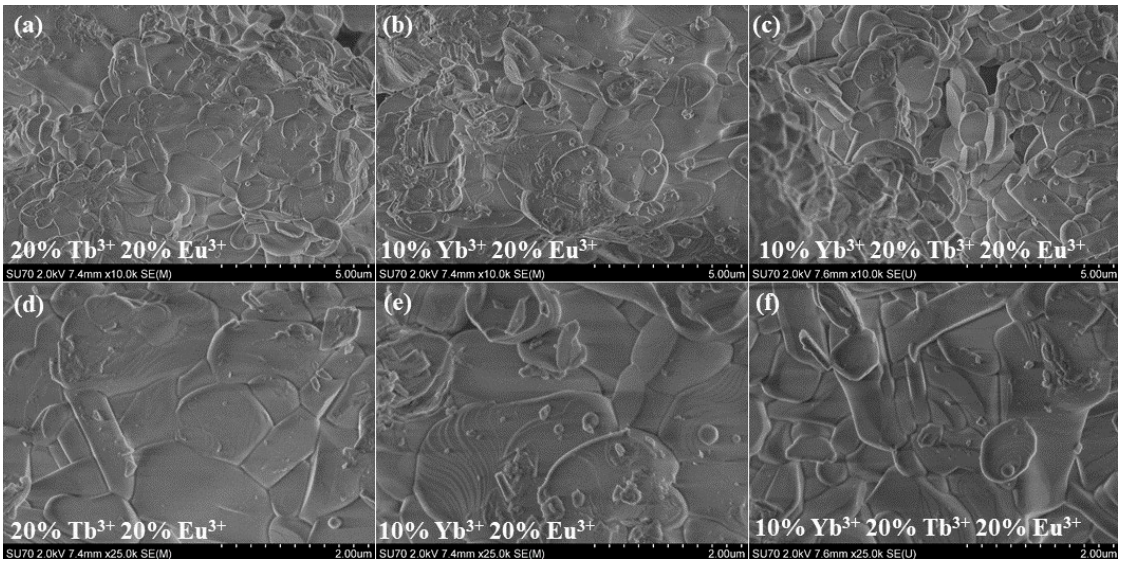


Figure S3. SEM images of KGPW:20%Tb^{3+},20%Eu^{3+} (a) and (d), KGPW:10%Yb^{3+},20%Eu^{3+} (b) and (e), KGPW:10%Yb^{3+},20% Tb^{3+},20%Eu^{3+} (c) and (f) under different magnification.

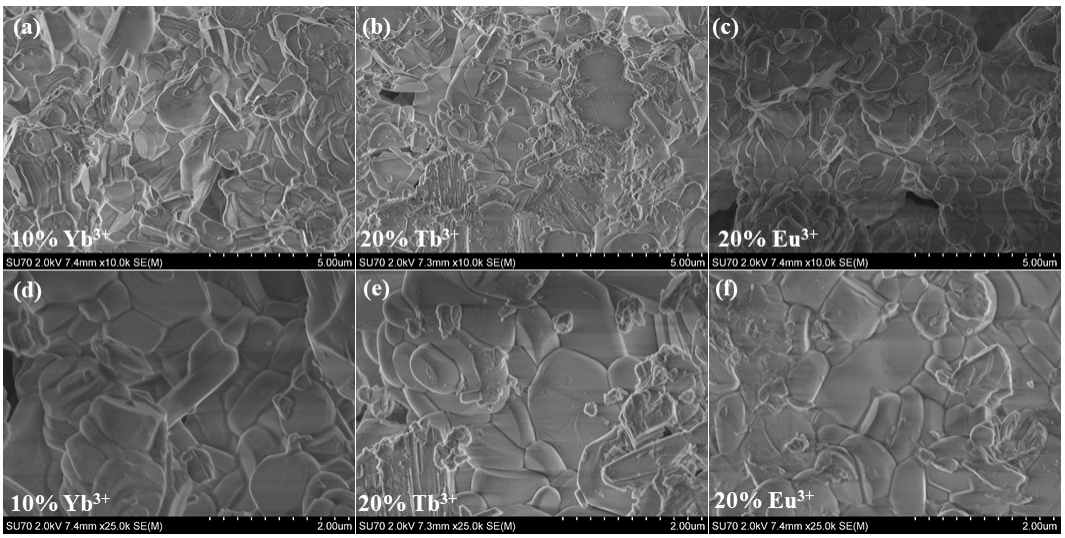


Figure S4. SEM images of the KGPW:10%Yb^{3+} (a) and (d), KGPW:20%Tb^{3+} (b) and (e), KGPW:20%Eu^{3+} (c) and (f).

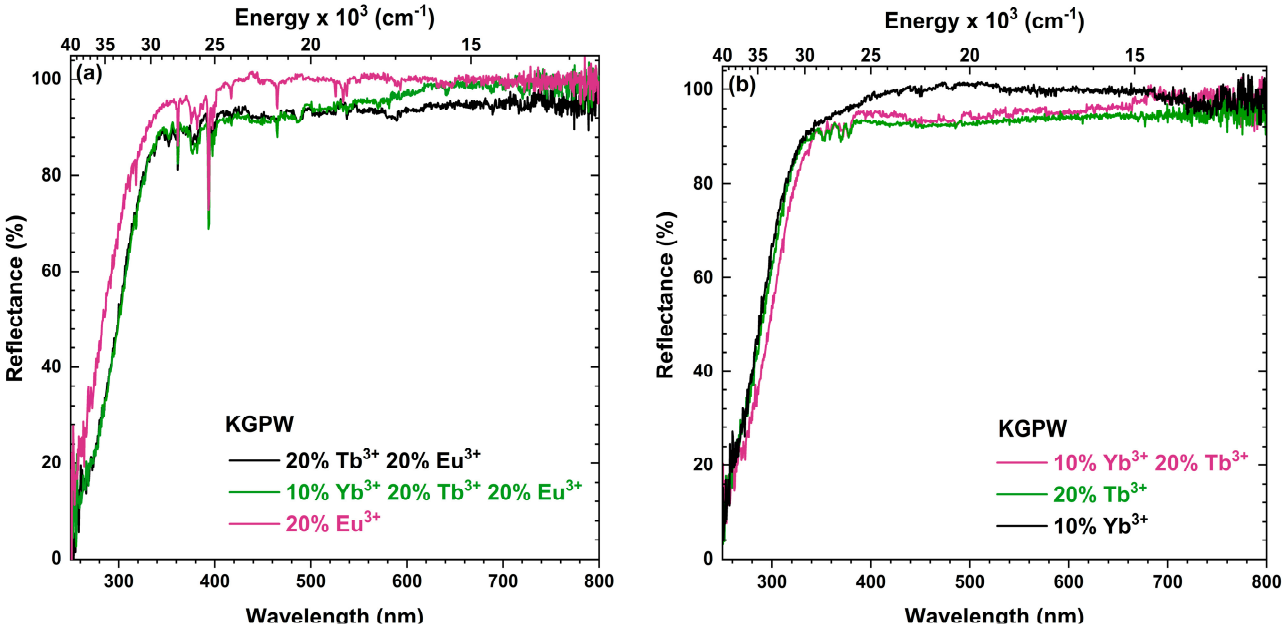


Figure S5. Reflection spectra of KGPW:20%Tb^{3+},20%Eu^{3+} (black line), KGPW:10%Yb^{3+},20%Tb^{3+},20%Eu^{3+} (green line), and KGPW:20%Eu^{3+} (red line) (a). KGPW:10%Yb^{3+},20%Tb^{3+} (red line), KGPW:20%Tb^{3+} (green line), and KGPW:10%Yb^{3+} (black line) (b).

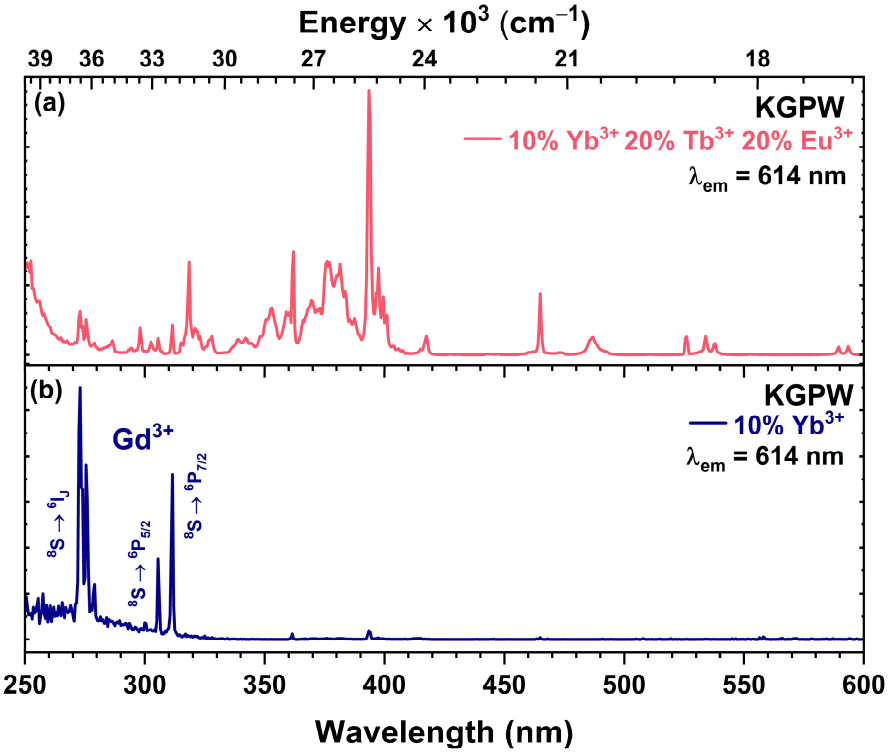


Figure S6. Excitation spectra (λ_{em} = 614 nm) of KGPW doped with (a) 10%Yb^{3+},20% Tb^{3+},20%Eu^{3+}, and (b) doped with 10% Yb^{3+}.

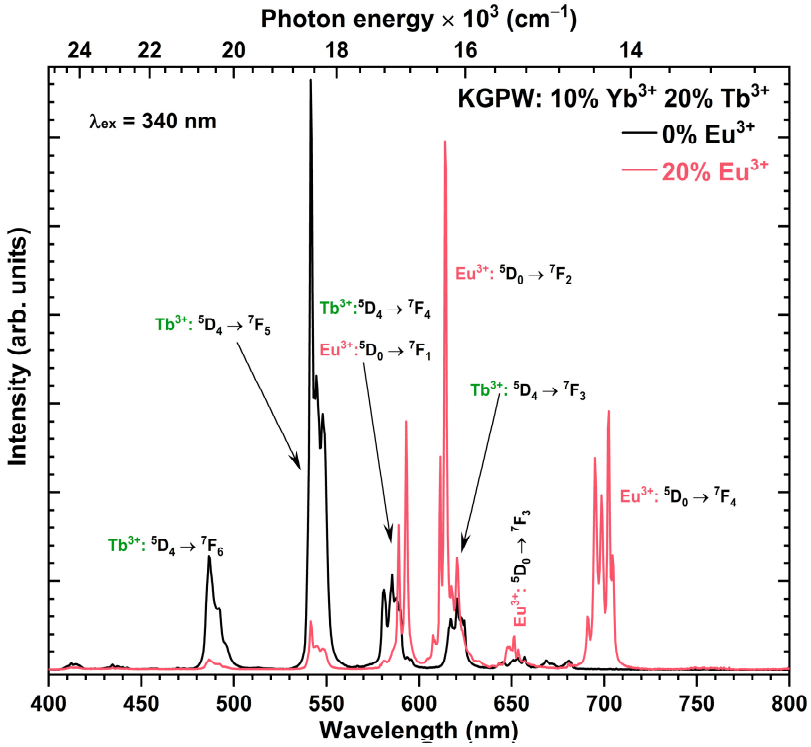


Figure S7. Emission (λ_{ex} = 340 nm) spectra of KGPW:10%Yb^{3+},20%Tb^{3+},Eu^{3+} as a function of Eu^{3+} concentration.

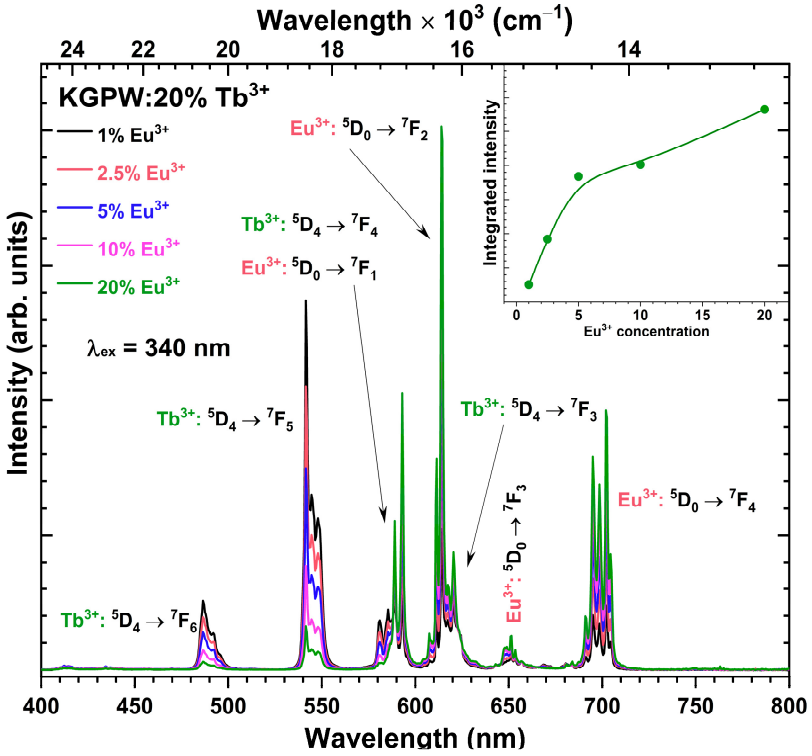


Figure S8. Emission spectra of KGPW:20%Tb³⁺,Eu³⁺ as a function of Eu³⁺ concentration (λex = 340 nm). The inset graph shows integrated emission intensity as a function of Eu³⁺ concentration.

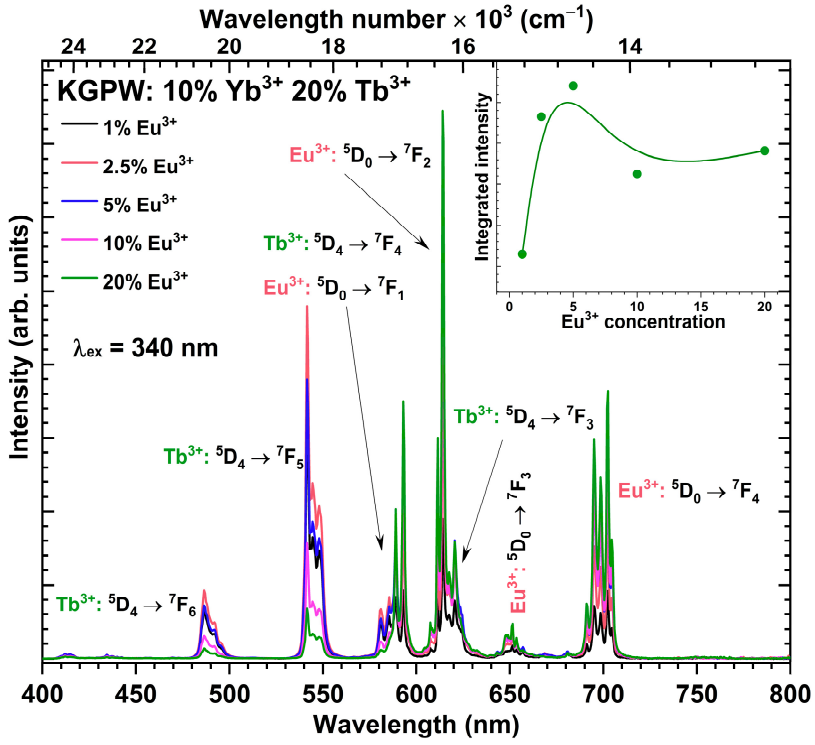


Figure S9. Emission spectra of KGPW:10%Yb³⁺,20%Tb³⁺,Eu³⁺ as a function of Eu³⁺ concentration (λex = 340 nm). The inset graph shows integrated emission intensity as a function of Eu³⁺ concentration.

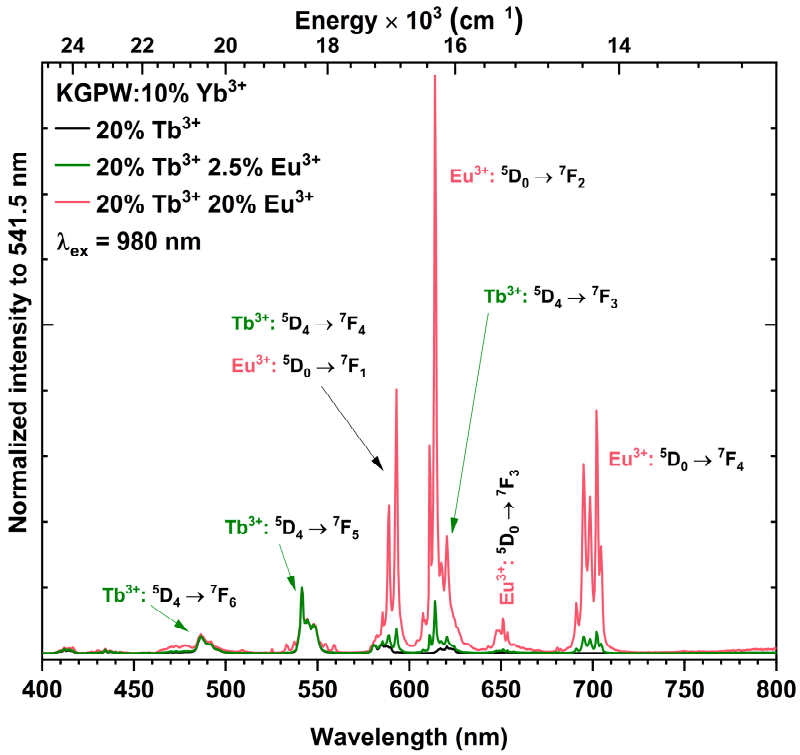


Figure S10. UC emission spectra (normalized to 541.5 nm) of KGPW:10%Yb³⁺,20%Tb³⁺, KGPW:10%Yb³⁺,20%Tb³⁺,2.5%Eu³⁺, and KGPW:10%Yb³⁺,20%Tb³⁺,20%Eu³⁺ (λ_{ex} = 980 nm).

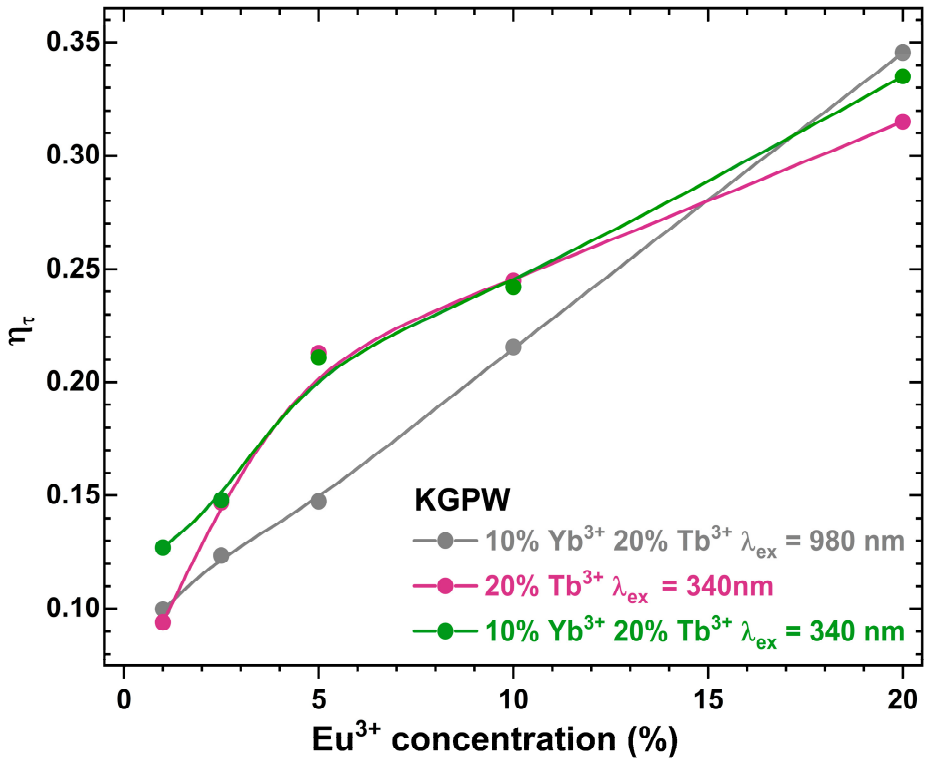


Figure S11. Tb^{3+} → Eu^{3+} energy transfer efficiency as a function of Eu^{3+} concentration.

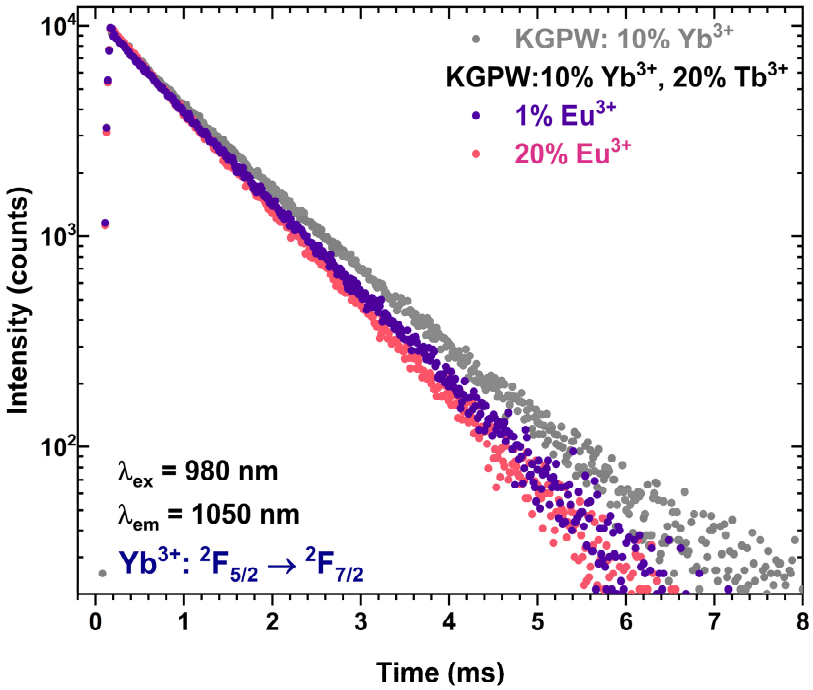


Figure S12. Yb^{3+} PL decay curves (λ_{ex} = 980 nm, λ_{em} = 1050 nm) in KGPW:10%Yb^{3+} and KGPW:10%Yb^{3+},20%Tb^{3+} samples as a function of Eu^{3+} concentration.

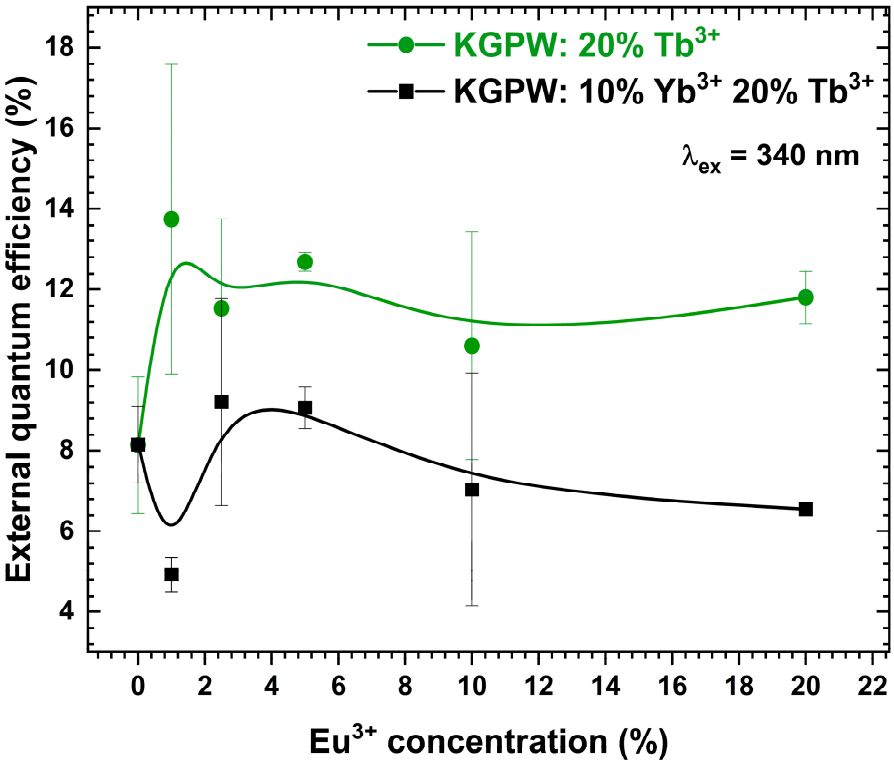


Figure S13. External quantum efficiency of all synthesized samples as a function of Eu^{3+} concentration (λ_{ex} = 340 nm).