

Electronic Supplementary Information

Multi-Package Purplish White LED lightings for Optimizing the Photosynthesis Performance and Vision-friendly Quality

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Experimental

Synthesis of narrow-band red-emitting $\text{K}_2\text{SiF}_6\text{:Mn}$ phosphor:^{S1} In order to synthesize the red-emitting $\text{K}_2\text{SiF}_6\text{:Mn}^{4+}$ phosphor, pure SiO_2 powders were dissolved in HF (25 vol%) at room temperature for 2 hours to form a H_2SiF_6 solution. A stoichiometric amount of KMnO_4 was dissolved in the H_2SiF_6 solution. After the color of the solution changed from colorless to a deep purple, H_2O_2 (30 vol%) was added drop-by-drop. The solution formed a yellow precipitate of $\text{K}_2\text{SiF}_6\text{:Mn}$ powders. After finishing the reaction, the powders were filtered and dried in the oven.

Fabrication of long wavelength pass dichroic filter (LPDF):^{S2-S5} LPDFs were fabricated using e-beam evaporator by depositing proper thickness of TiO_2 and SiO_2 nano-multilayeres. LPDFs were designed using the characteristic matrix method to simulate the reflectance, transmittance and absorption. In this study, two types of LPDFs (L535, and L550; 535 and 550 nm at the half-band-edge wavelength, respectively) were fabricated as a capping filter for green/yellow (L535) and amber/red (L550) monochromatic pc-LEDs.

S1 C. Liao, R. Cao, Z. Ma, Y. Li, G. Dong, K. N. Sharafudeen, and J. Qiu, *J. Am. Ceram. Soc.*, 2013, **96**(11), 3552-3556.

S2 J. H. Oh, J. R. Oh, H. K. Park, Y.-G. Sung and Y. R. Do, *Opt. Express* 2011, **19**, A270-A279.

S3 J. R. Oh, S.-H. Cho, J. H. Oh, Y.-K. Kim, Y.-H. Lee, W. Kim and Y. R. Do, *Opt. Express* 2011, **19**, 4188-4198.

S4 J. H. Oh, S. J. Yang, Y.-G. Sung and Y. R. Do, *Opt. Express* 2012, **20**, 20276-20285.

S5 J. H. Oh, S. J. Yang and Y. R. Do, *Light: Sci. Appl.* 2014, **3**, e141.

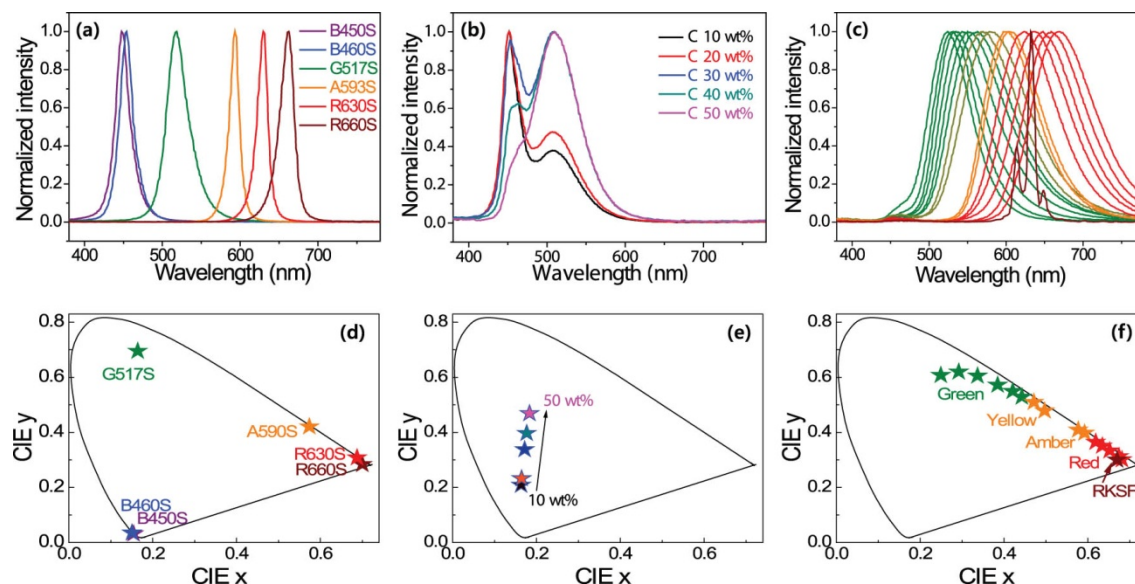


Figure S1. Normalized PL spectra of (a) six semiconductor LEDs (two blue, one green, one amber and two red), (b) five partially converted cyan phosphor-coated blue LEDs with various wt% from 10 to 50 and (c) sixteen LPDF-capped, monochromatic pc-LEDs (six green, two yellow, two amber and six red). 1931 CIE color coordinates of (d) six semiconductor LEDs, (e) five partially converted cyan phosphor-coated blue LEDs with various wt% from 10 to 50 and (g) sixteen LPDF-capped, monochromatic pc-LEDs.

Table S1a. Figures of merit for visual performance and photosynthesis performance of the monochromatic pc-LEDs and semiconductor LEDs.

	LER	LE	EQE	PLER	PLE	PAF
	lm/W	lm/W		plm/W	plm/W	plm/lm
B450S	41	16	0.40	634	251	15.60
B460S	45	17	0.38	633	241	13.95
G517S	456	63	0.14	339	47	0.74
A593S	487	54	0.11	381	41	0.78
R630S	209	68	0.33	478	158	2.27
C10wt%	205	81	0.39	517	203	2.52
C20wt%	221	86	0.39	506	196	2.28
C30wt%	285	102	0.36	461	165	1.62
C40wt%	315	106	0.34	440	148	1.40
C50wt%	349	107	0.31	416	128	1.19
G515	466	156	0.33	351	118	0.75
G521	499	176	0.35	334	118	0.67
G530	506	192	0.38	332	126	0.66
G540	491	196	0.40	340	135	0.69
G550	475	185	0.39	347	135	0.73
G560	462	186	0.4	354	143	0.77
Y570	444	180	0.41	363	147	0.82
Y580	402	164	0.41	378	154	0.94
A590	330	129	0.39	414	162	1.26
A600	305	101	0.33	423	140	1.39
R630	220	69	0.31	436	136	1.98
R640	168	53	0.31	432	135	2.56
R650	123	40	0.33	425	140	3.47
R660	81	28	0.35	407	142	5.03
R670	57	18	0.32	380	121	6.70
RKSF	194	64	0.33	482	159	2.49

Table S1b. Figures of merit for photo-pigmented photosynthesis performance of the monochromatic pc-LEDs and semiconductor LEDs.

	PpLER (pplm/W)					PpLE (pplm/W)				
	CLa	CLb	β -CT	PE	PC	CLa	CLb	β -CT	PE	PC
B450S	107	299	381	15	18	42	118	151	6	7
B460S	65	328	392	16	15	25	125	149	6	6
G517S	5	16	54	274	94	1	2	8	38	13
A593S	27	21	3	130	491	3	2	0	14	53
R630S	54	94	1	6	461	18	31	0	2	152
C10wt%	42	177	257	119	54	17	70	101	47	21
C20wt%	38	162	244	129	58	15	63	94	50	22
C30wt%	22	111	193	170	73	8	40	69	61	26
C40wt%	16	86	169	189	80	5	29	57	64	27
C50wt%	10	60	142	211	89	3	18	44	65	27
G515	8	26	65	297	144	3	9	22	99	48
G521	9	21	40	321	179	3	7	14	113	63
G530	14	21	26	321	215	5	8	10	122	81
G540	20	24	19	303	252	8	9	7	121	100
G550	26	25	12	284	278	10	10	5	111	109
G560	29	28	12	269	296	12	11	5	108	119
Y570	34	30	7	248	316	14	12	3	101	128
Y580	41	35	9	208	324	17	14	4	85	132
A590	56	43	5	117	372	22	17	2	46	146
A600	60	46	3	96	368	20	15	1	32	122
R630	74	52	4	48	310	23	16	1	15	97
R640	80	50	3	30	256	25	16	1	9	80
R650	84	49	2	16	204	28	16	1	5	67
R660	84	43	2	5	149	29	15	1	2	52
R670	78	36	1	3	107	25	11	0	1	34
RKSF	63	105	10	7	414	21	34	3	2	136

Photo-pigmented efficacy (PpLER and PpLE)

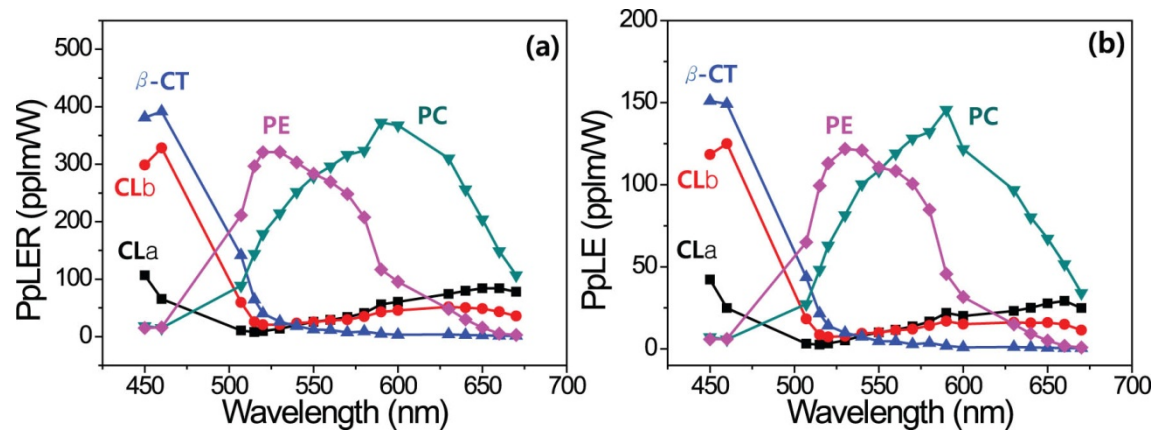


Figure S2. Figures of merits of each blue LED and cyan/green/amber/red LPDF-capped pc-LEDs from 450 nm to 670 nm two kinds of PLE, (a) PpLER and (b) PpLE of five different photo-pigments (CLa, CLb, β -CT, PE and PC).

Commercialized types of lighting and daylight

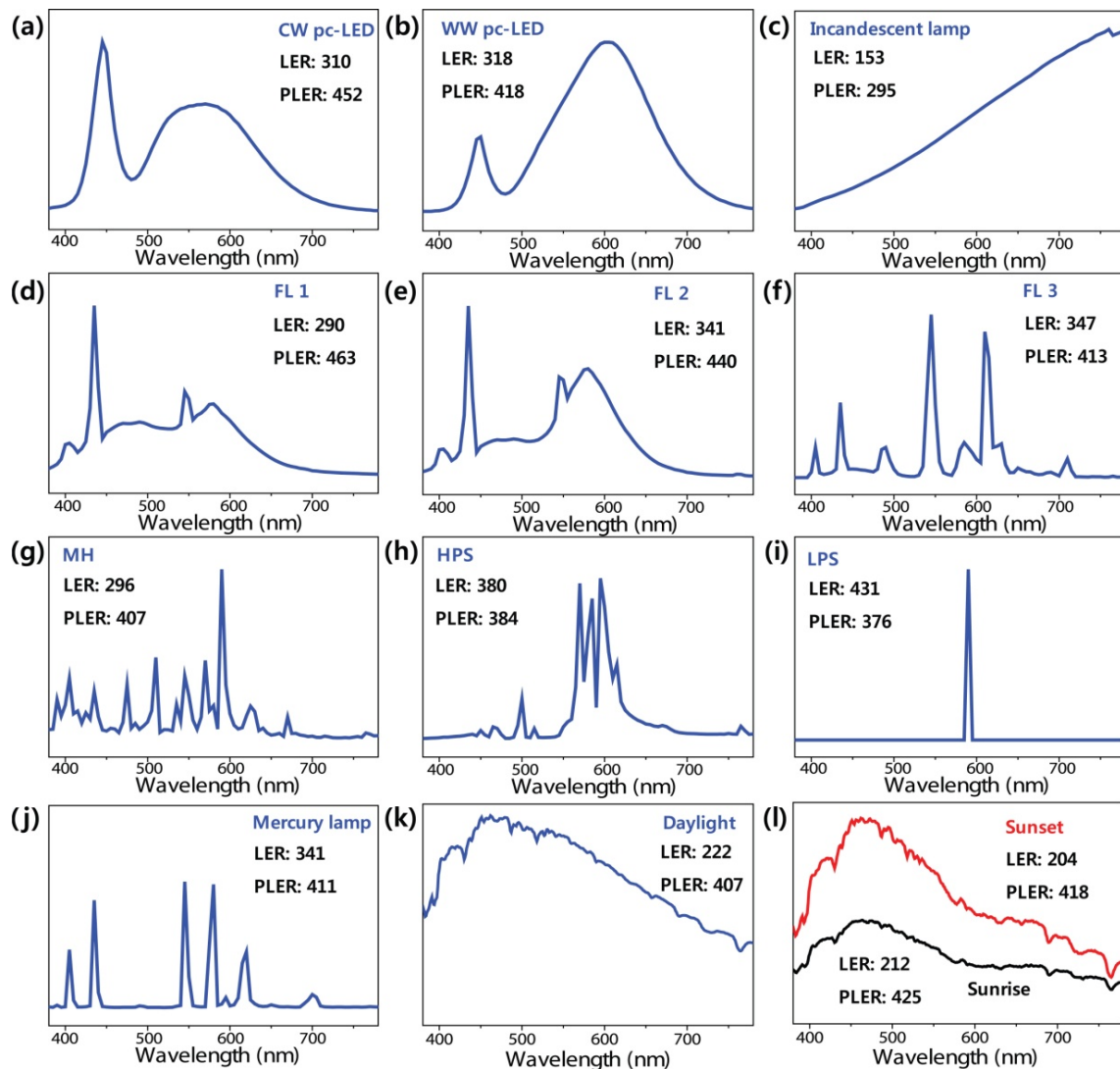


Figure S3. Normalized spectral power distributions of 10 commercialized types of lighting and daylight. (a) a CW pc-LED (cool-white pc-LED), (b) WW pc-LED (warm-white pc-LED), (c) an incandescent lamp, (d) an FL 1 (halophosphate FL, 6,480 K), (e) an FL 2 (halophosphate FL, 4,290 K), (f) an FL 3 (triphosphor FL, 3,380 K), (g) an MH (metal-halide), (h) an HPS lamp (high-pressure sodium), (i) an LPS lamp (low-pressure sodium), (j) a mercury lamp, (k) daylight, and (l) sunrise and sunset

Table S2a. Figures of merit for visual performance and photosynthesis performance of 10 commercialized type of lighting and daylight.

	LER	LE	EQE	PLER	PLE
	lm/W	lm/W		plm/W	plm/W
CW pc-LED	310	98	0.32	452	145
WW pc-LED	318	98	0.31	418	130
Incandescent	153	26	0.17	295	50
FL-1	290	63	0.22	463	102
FL-2	341	63	0.18	440	81
FL-3	347	63	0.18	413	75
MH	296	90	0.30	407	124
HPS	380	120	0.32	384	121
LPS	431	120	0.28	376	105
Mercury lamp	341	60	0.18	411	72
Daylight	222	-	-	407	-
Sunset	204	-	-	418	-
Sunrise	212	-	-	425	-

Table S2b. Figures of merit for photo-pigmented photosynthesis performance of 10 commercialized type of lighting and daylight.

	PpLER (pplm/W)					PpLE (pplm/W)				
	CLa	CLb	β -CT	PE	PC	CLa	CLb	β -CT	PE	PC
CW pc-LED	66	99	125	163	197	21	32	40	52	63
WW pc-LED	56	61	46	150	267	17	19	14	47	83
Incandescent	41	30	24	70	132	7	5	4	12	22
FL-1	88	83	148	159	173	19	18	32	35	38
FL-2	81	69	111	184	225	15	13	21	34	42
FL-3	65	50	74	176	273	12	9	14	32	50
MH	69	47	94	172	224	21	14	28	52	68
HPS	34	32	22	186	372	11	10	7	59	118
LPS	23	20	0	117	506	6	6	0	33	141
Mercury lamp	99	48	85	225	254	17	8	15	40	45
Daylight	66	69	113	115	138	-	-	-	-	-
Sunset	68	76	130	106	117	-	-	-	-	-
Sunrise	68	78	133	112	121	-	-	-	-	-

Current and temperature dependence of LEDs

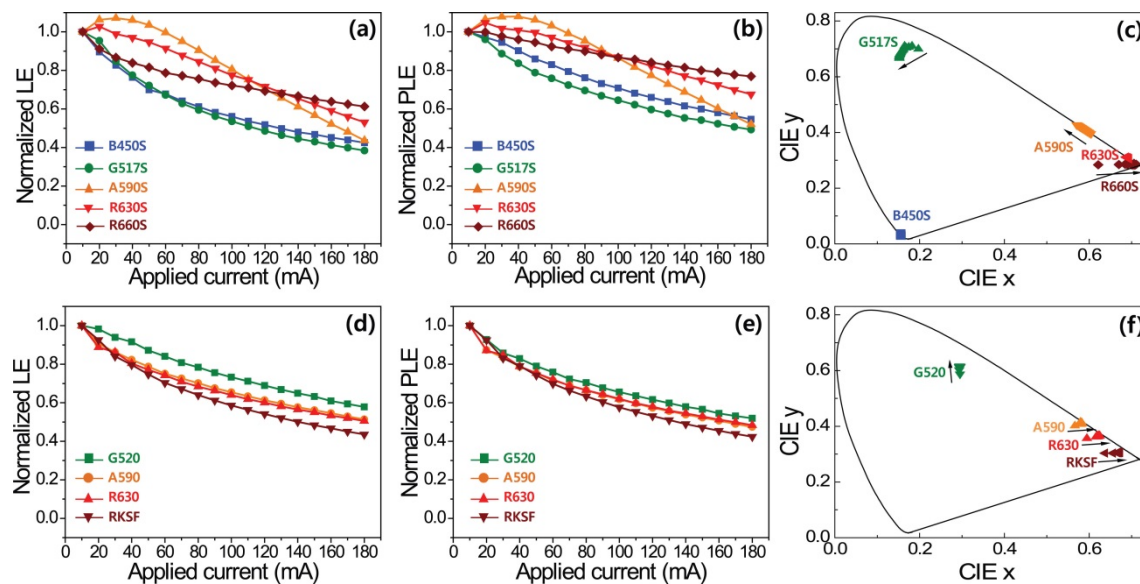


Figure S4. (a) Normalized LE, (b) normalized PLE and (c) 1931 CIE color coordinates of semiconductor type LEDs (B450S, G517S, A590S, R630S and R660S) as a function of the applied current. (d) Normalized LE, (e) normalized PLE and (g) 1931 CIE color coordinates of LPDF-capped monochromatic pc-LEDs (G520, A590, R630 and RKSF) as a function of the applied current.

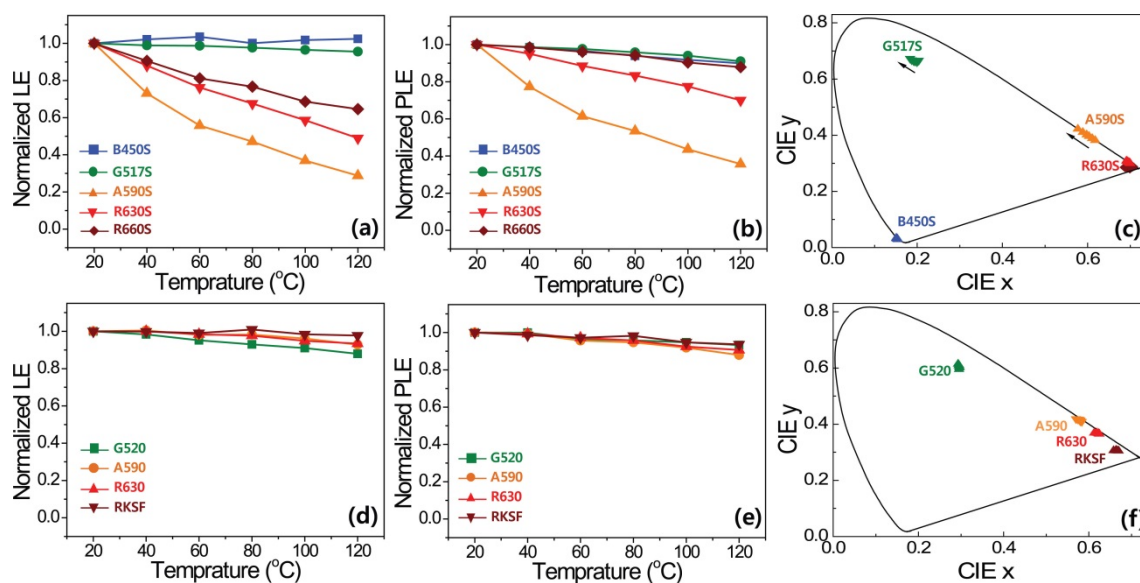


Figure S5. (a) Normalized LE, (b) normalized PLE and (c) 1931 CIE color coordinates of RAGB semiconductor type LEDs (B450S, G517S, A590S, R630S and R660S) as a function of the temperature. (d) Normalized LE, (e) normalized PLE and (g) 1931 CIE color coordinates of LPDF-capped monochromatic pc-LEDs (G520, A590, R630 and RKSF) as a function of the temperature.

Photo-pigmented efficacy (PpLER and PpLE)

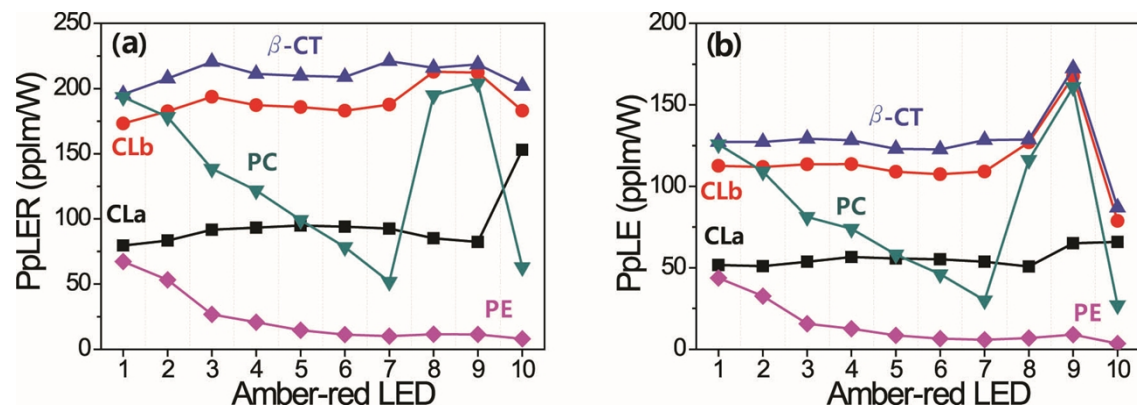


Figure S6. (a) PpLER and (b) PpLE of blue and amber or red dichromatic LEDs with changing the amber and red LEDs. Sample number 1, A590/B450S; 2, A600/B450S; 3, R630/B450S; 4, R640/B450S; 5, R650/B450S; 6, R660/B450S; 7, R670/B450S; 8, RKSF/B450S; 9, R630S/B450S; 10, R660S/B450S.