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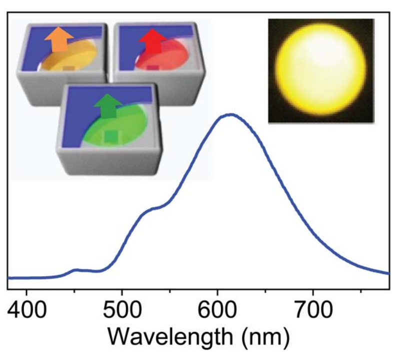

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High-Color-Quality Multipackage Phosphor-Converted LEDs for Yellow Photolithography Room Lamp

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Abstract: This paper introduces a multi-package light-emitting diode (LED) system with the ability to realize an efficient and good color quality yellow room lamp under a photolithography environment. Various yellow room LEDs were fabricated by combining two, three, and four packages among green (G), yellow (Y), amber (A), and red (R) phosphor-converted LEDs (pc-LEDs) capped with long-wavelength pass dichroic filters (LPDF). The values of luminous efficacy (LE), color rendering index (CRI), and color quality scale (CQS) of the nine combinations of multi-package pc-LEDs are compared and optimized for application to a yellow room lamp. The optical properties of the selected G-A-R multi-package LED are compared with those of fluorescent light tubes (FT) and a yellow fluorescent light tube (YFT), which are generally used in photolithography rooms. The proposed G-A-R multi-package LED provides high luminous efficacy of 100 lm/W and good color quality (CRI of 78 and CQS of 36) at correlated color temperature (CCT) and color coordinates similar to those of currently commercialized YFTs.

Index Terms: Advanced optics design, light emitting diodes (LEDs), color rendering index (CRI).

1. Introduction

Photolithography is an important technology for micro/nanofabrication; it is used to transfer designed patterns to photoresist (PR) layers coated on a substrate with the help of a photomask. The photolithographic technique consists of several consecutive processes: substrate cleaning, PR coating, ultraviolet (UV) exposure, development, pattern transfer, and stripping processes [1], [2]. Since most PRs are light-sensitive materials, lamps for any photolithographic environment must not include light from the wavelength region from UV to greenish blue ($<$ 500 nm), which is the wavelength range that PRs are sensitive to [see Fig. 1(a)] [3].

Fig. 1(b)–(c) show the spectral power distributions (SPDs) and the 1931 Commission Internationale d'Eclairage (CIE) color coordinates of a fluorescent light tube (FT) and an yellow fluorescent light tube (YFT) [4], [5]. In a photolithographic environment, a so-called “yellow room,” there is usually a yellow light to prevent the initiation of a photoreaction of PR; this light is made by filtering the wavelength regions shorter than 500 nm and using only yellow emitting materials. Hence, yellow room lamps cannot render the real colors blue or red due to the lack of blue and red wavelengths in the emitting peaks of currently used yellow fluorescent lamps. This means

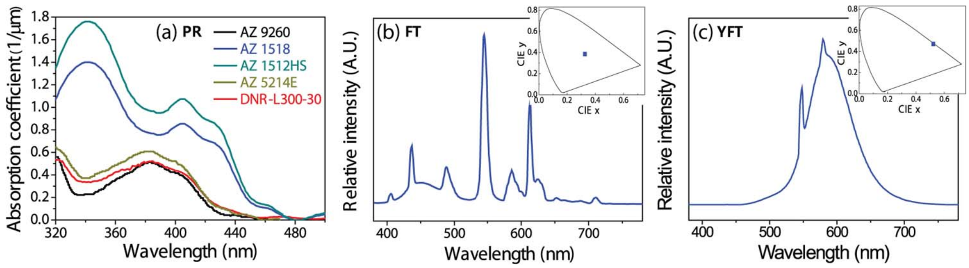

Fig. 1. (a) Spectral sensitivity of various commercialized photoresists [3] and spectral power distributions of (b) Fluorescent light tube (FT) (TL-D32W/865RS, Philips) and (c) Yellow fluorescent light tube (YFT) (FL40Y, Wooree Lighting Co. Ltd.) (Insets: 1931 Commission Internationale d'Eclairage (CIE) color coordinates).

that yellow room lamps have a low color rendering index (CRI) and color quality scale (CQS); therefore, when researchers are working in a photolithographic yellow room, high color-quality lamps should be considered in order to distinguish colors more accurately. Also, a wider emission band for yellow lamps could make it possible to improve the CRI and CQS, which determine the color quality of any lamp [6]–[8].

Most yellow rooms use YFTs contain mercury-vapor and yellowish-orange phosphors and consume a lot of power. These days, there is a growing tendency to replace general FTs and incandescent lamps with white phosphor-converted LEDs (pc-LEDs) due to the many advantages of LEDs such as low power consumption, long life time, eco-friendliness, and fast response time [9], [10]. Likewise, if YFTs are replaced by LEDs designed for use as yellow room lamps, it will be possible to keep the environment clean, save energy [2], and further improve the designed color quality of yellow lamps. However, the semiconductor-type LEDs have many problems such as low CRI values due to their narrow emission band and low efficiency in the green to amber wavelength region: the so-called "green gap." Also, multi-package semiconductor-type LEDs show large variations of each colored LED with their color coordinates and droop properties at different current and temperature.

Previously, we reported various highly efficient, green (G), yellow (Y), amber (A), and red (R) pc-LEDs that were capped with long-wavelength pass dichroic filters (LPDF) in order to enhance the luminous efficacy (LE) and realize pure monochromatic color with low phosphor concentrations in the "green gap" range of wavelength [11]–[14]. As previously reported in our publications, healthy, natural, efficient, and tunable multi-package white LEDs can be realized by combining a blue LED and G, A, and R pc-LEDs [8], [15]. This simple concept can lead to the possibility of fabricating efficient and good color quality multi-package yellow LEDs by combining various monochromatic G, Y, A, and R pc-LEDs without a blue LED.

In this study, we optimize multi-package yellow room LED lamps by combining two, three, and four LPDF-capped, monochromatic G, Y, A, and R pc-LEDs in order to realize a highly efficient and good color quality LED lamp that can be used in a photolithography environment due to their high efficiency and broad band emitting (69 nm–115 nm) G, Y, A, and R pc-LEDs. Additionally, owing to their wide emission spectrum of mixed yellow peaks, these multi-package yellow LED lamps will provide a clearer work environment, with better color distinguishability, to researchers and workers who work in photolithographic yellow rooms.

2. Experimental Details

Fabrication of long-wavelength-pass dichroic filter (LPDF) [8], [11], [15]: For the design of the LPDF multilayer film, the characteristic matrix method was used to simulate the reflectance, transmittance, and absorption. For fabrication of the stacks, terminal eight-wave-thick TiO_2 and quarter-wave-thick SiO_2 nano-multilayered films $(0.5TiO_2/SiO_2/0.5TiO_2)^9$ were coated onto glass substrates by e-beam evaporation at 250°. The transmittance and reflectance spectra of the LPDFs were controlled by changing the thickness of the TiO_2 and SiO_2 layers.

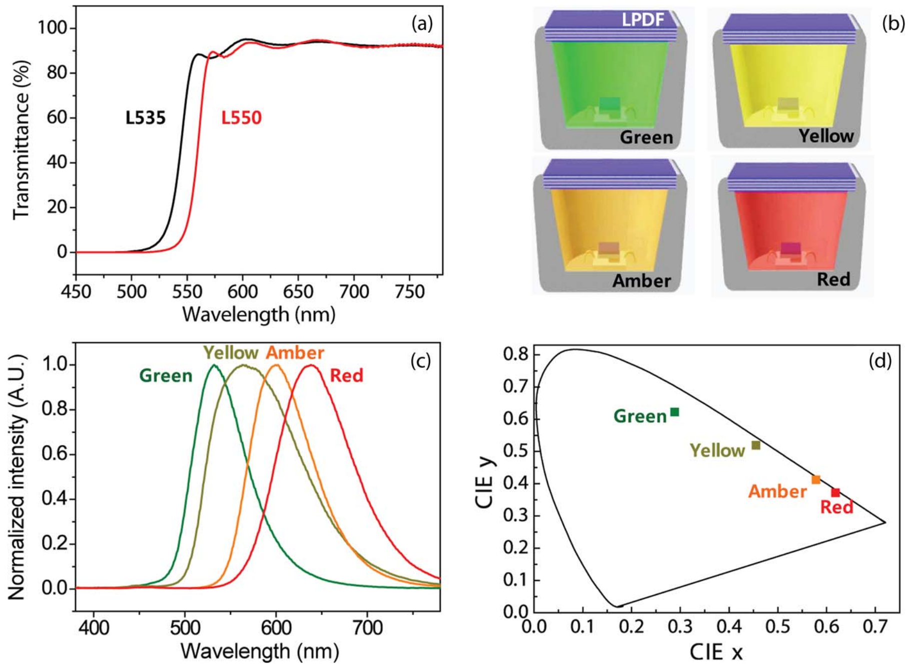

Fig. 2. (a) Transmittance spectra of two kinds of LPDFs (L535 and L550). (b) Cross-sectional schematic diagrams of LPDF-capped G, Y, A, and R pc-LEDs. (c) Electroluminescent spectra. (d) 1931 CIE color coordinates of G, Y, A, and R LPDF-capped monochromatic pc-LEDs at 250 mA.

Fig. 2(a) shows the transmittance of the LPDFs (L535 for green and L550 for yellow, amber, and red pc-LEDs).

Fabrication of LPDF-capped G, Y, A, and R pc-LEDs [8], [11], [15]: Green $[(Ba,Sr)_2SiO_4 : Eu]$, amber $[(Ba,Ca,Sr)_3SiO_5 : Eu]$, and red $[(Ca,Sr)AlSiN_3 : Eu]$ powder phosphors were purchased from Intematix Corporation and yellow $(Y_3Al_5O_{12} : Ce, YAG)$ powder phosphors were purchased from Merck. An InGaN blue LED $(\lambda_{max} = 445\ nm)$ was used as an excitation source for the phosphors of the G, Y, A, and R pc-LEDs. The blue LED packages were purchased from Dongbu LED, Inc. In order to make the phosphor paste, proper amounts of the phosphors were mixed with Si-binder (KER-2500A, B) and toluene. The green, yellow, amber, and red phosphor pastes were put into an InGaN blue LED package and hardened in an oven at 150° for 1 h. After hardening, the LPDFs were capped on the LED cup. Fig. 2(b) shows schematic diagrams of LPDF-capped pc-LEDs. The G pc-LED was capped with LPDF of L535; the Y, A, and R pc-LEDs were capped with LPDF of L550. Fig. 2(a) shows the transmittance spectra of the two types of LPDFs, determined using a UV-visible light spectrometer (S-3100; SINCO Co., Ltd.).

Characterization of LPDF-capped G, Y, A, and R pc-LEDs and multi-package yellow room LED lamp: The emission spectra and luminous flux of the LPDF-capped G, Y, A, and R pc-LEDs were measured in an integrating sphere using a spectrophotometer (Darsapro-5000; PSI Co., Ltd.) with an applied current of 250 mA. The electroluminescence (EL) spectra and the 1931 CIE color coordinates of the LPDF-capped G, Y, A, and R pc-LEDs are shown in Fig. 2(c) and (d). Also, the resultant optical properties of the G, Y, A, and R pc-LEDs are summarized in Table 1. In order to compare the optical properties of YFT and multi-package yellow-room LED lamps with similar values of correlated color temperature (CCT) and similar 1931 CIE color coordinates, the SPDs and luminous flux of the multi-package yellow room LED lamps were also measured in an integrated sphere using a spectrophotometer (Darsapro-5000; PSI Trading Co., Ltd.). This occurred while controlling the applied current of each primary LED, with a total current of 500 mA for two packages, 750 mA for three packages, and 1000 mA for four packages. The luminous flux, the CRI, and the 1931 CIE color coordinates were calculated using the

TABLE 1
Optical properties of LPDF-capped monochromatic pc-LEDs

	Color coordinates		LE	DWL	BAND-W	Purity
	CIE x	CIE y	(lm/W)	(nm)	(nm)	-
Green (G)	0.320	0.617	165	532	69	79
Yellow (Y)	0.465	0.517	181	565	115	95
Amber (A)	0.581	0.412	119	600	81	98
Red (R)	0.640	0.351	55	639	96	97

Darsapro-5000 program. We also compared the color rendition using the Gretag Macbeth Color Checker Color Rendition Chart (Xrite Color Checker Chart).

Among various figures of merit for color assessment, CRI has been widely used for color-quality evaluation of lighting. However, not all high-CRI lighting devices can realize highly saturated color because the value of CRI is calculated using eight unsaturated test color samples $(R_1 - R_8)$. For this reason, in order to realize high color-quality lighting, we added the figure of merit of CQS, which is calculated using 15 test color samples (Munsell samples) and saturation factor, as previously reported [6]–[8].

3. Results

As can be seen in the schematic diagrams in the insets of Fig. 3(a)–(i), in order to compare the optical properties of multi-package yellow-room LED lamps, we fabricated nine combinations of multi-package yellow room LED lamps by combining two, three, and four LPDF-capped, monochromatic G, Y, A, and R pc-LEDs. We classified the nine combinations of multi-package yellow room LED lamps into three groups of white LEDs, so as to explain their optical properties more conveniently; the groups were as follows: green series (G-A, G-R two packages, and G-A-R three packages), yellow series (Y-A, Y-R two packages, and Y-A-R three packages), and green-yellow series (G-Y-A, G-Y-R, and G-Y-A-R four packages). Here, all yellow LEDs are denoted as combinations of colors.

Fig. 3 and Table 2 show the measured SPDs and the optical properties of the nine combinations of multi-package yellow-room LED lamps at room temperature. To prevent activating the photochemical reactions of the PR, all SPDs had no blue emission. The optical properties (LE, CRI, and CQS) of the nine combinations of multi-package yellow-room LED lamps showed higher values than did those of the YFLs. The CQS values of the green, yellow, and green-yellow series were 26–41, 15–23, and 16–30, respectively. The combinations without the R pc-LED show low CRI values due to the lack of reddish emission (G-A, Y-A, and G-Y-A). In the green series, the CRI value of the G-R two-package and the G-A-R three-package yellow-room LED lamps are even higher than that of the white FT $(\text{CRI} = 72)$. The Y-A [see Fig. 3(d)] two-package LED shows the highest LE because the applied current of the Y and A pc-LEDs are almost identical to the rated current; however, this package has the lowest CRI value among the nine combinations of monochromatic pc-LEDs without blue LED, due to the minimal widening of the mixed emission peak. From the nine possible combinations, we selected one G-A-R combination as the best multi-package yellow-room LED lamp because it offers good color quality (CRI = 78 and CQS = 36), as well as high LE (100 lm/W), even though there is no blue color in this yellow lamp.

Fig. 4 shows variations of the CIE color coordinates, luminous efficacy, CCT, and CRI of the selected G-A-R pc-LED lamp as functions of the applied current and ambient temperature.

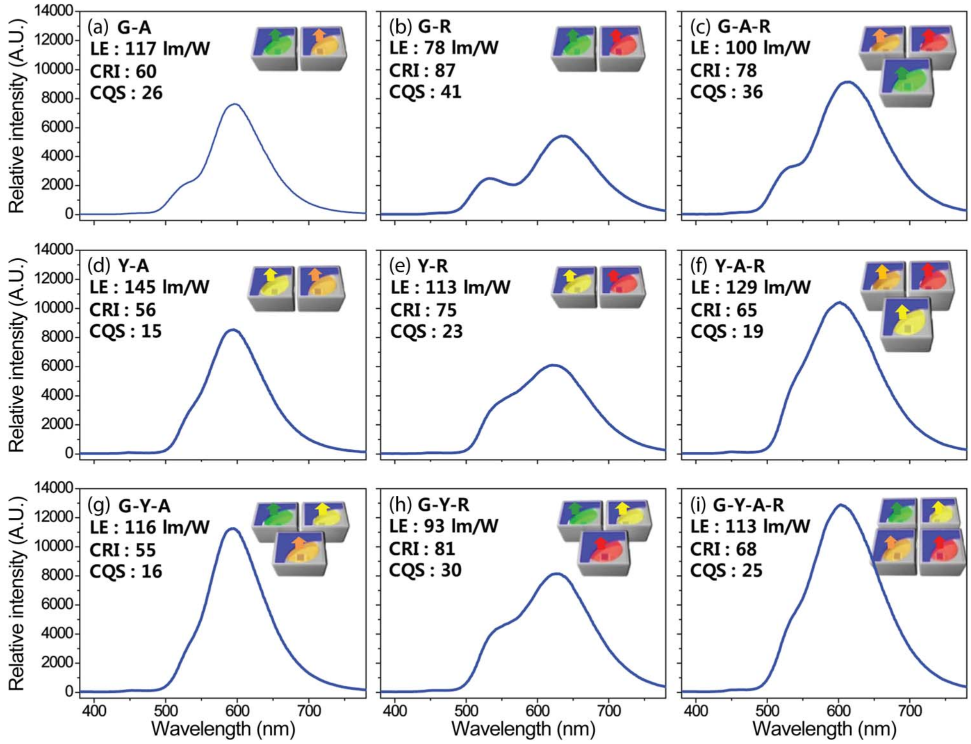

Fig. 3. Electroluminescent spectra of multi-package pc-LEDs combined with (a) G-A, (b) G-R, (c) G-A-R, (d) Y-A, (e) Y-R, (f) Y-A-R, (g) G-Y-A, (h) G-Y-R, and (i) G-Y-A-R. The insets are the schematic diagrams of the various multi-package LEDs.

TABLE 2

Optical properties of FT, YFT, and nine combinations of multi-package yellow room lamps

		Color coordinates		CCT	LE	LER	CRI	CQS
		CIE x	CIE y	(K)	(lm/W)	(lm/W)	(R_a)	(Q_a)
	FT	0.333	0.380	5,480	55-70[a]	348	72	74
	YFT	0.516	0.476	2,497	70-90[b]	454	38	5
Green series	G-A	0.527	0.456	2,268	117	378	60	26
	G-R	0.520	0.451	2,302	78	256	87	41
	G-A-R	0.533	0.447	2,147	100	307	78	36
Yellow series	Y-A	0.525	0.464	2,332	145	386	56	15
	Y-R	0.526	0.460	2,297	113	305	75	23
	Y-A-R	0.523	0.464	2,353	129	350	65	19
Green-Yellow Series	G-Y-A	0.529	0.460	2,270	116	384	55	16
	G-Y-R	0.524	0.458	2,299	93	293	81	30
	G-Y-A-R	0.529	0.456	2,250	113	334	68	25

[a] Phillips product catalog (USA).

[b]The LEs of YFTs was calculated from the external quantum efficiency (EQE) of FL using the following equation. (Eq. EQE = LE / LER) [16].

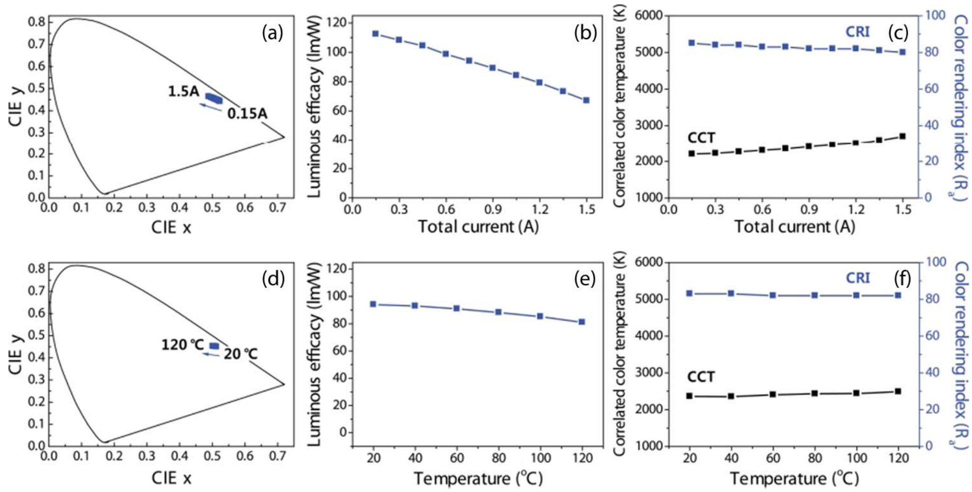

Fig. 4. Current dependence of the G-A-R pc-LED lamp. (a) CIE color coordinates, (b) luminous efficacy, and (c) CCT (left) and CRI (right). Temperature dependence of the G-A-R pc-LED lamp. (d) CIE color coordinates, (e) luminous efficacy, and (f) CCT (left) and CRI (right).

These figures show that the G-A-R pc-LED has acceptable variations of CCT and CRI with the increase of both applied current and ambient temperature. These variation trends are similar to those of commercialized single-package white pc-LEDs, as has been reported previously [8], [11].

In order to confirm that the selected combination of the G-A-R three-package yellow-room LED lamp would be acceptable for use in the photolithographic environment, we carried out a PR patterning test. The PR test was carried out as follows. Glass substrates were cleaned and UV-O_3 treated. The PR solution [DNR-L300-30, Dongjin Semichem Co., Ltd., see Fig. 1(a)], which is a negative PR, was spin-coated onto the glass substrates at 3000 rpm for 35 s, and the PR coated glass substrates were soft baked at 90 °C for 90 seconds. After the soft baking process, the substrates were exposed to a UV lamp for 7 s, to FT (TL-D32W/865RS, Philips) for 1 h, to YFT (FL40 Y, Wooree Lighting Co., Ltd.) for 1 h, and selected multi-package yellow room LED sets (LPDF-capped G, A, and R pc-LEDs) with illumination of 300 lux for 1 h, 72 h, and 168 h. The post baking process after UV exposure was carried out on a hot plate at 110 °C for 120 sec. The developing process was carried on with a developer (AZ 300, AZ Electronics Materials USA Corp.) for 60 s. Samples were then washed with distilled water. After photolithography, we deposited Al using a thermal evaporator, and removed the PR with acetone. We obtained Al line patterns and analyzed the dimensions and shapes of the Al patterns using optical microscopy (PSI 4RT; PSI Trading Co., Ltd.).

Fig. 5(a)–(f) provide optical microscope photographs of the PR-coated glass after the exposure and development processes. Similar to the PR pattern obtained under UV lamp illumination [see Fig. 5(a)], the patterned PR layer was obtained under an FT lamp by removing the photo-chemically reacted area with a developer. This was done because the exposed PR area under the opening region of the patterned photo-mask was photo-chemically reacted by some of the UV and blue emissions from the FT lamp. However, Fig. 5(c) and (f) show that the PR stayed intact after the exposure to the YFT and the G-A-R pc-LED lamps and after the developing processes. This means that both the YFL and the selected G-A-R pc-LED lamp do not initiate a photochemical reaction in the PR film. Hence, the G-A-R pc-LED lamp can be used as a yellow lamp in the photolithographic environment because, in the PR patterning test, our three-package pc-LED lamp obtained results similar to those obtained using a commercial yellow fluorescent lamp.

We also compared the color rendition using the Gretag Macbeth Color Checker Color Rendition Chart (Xrite Color Checker Chart). Fig. 6 provides photographs of the Color Checker

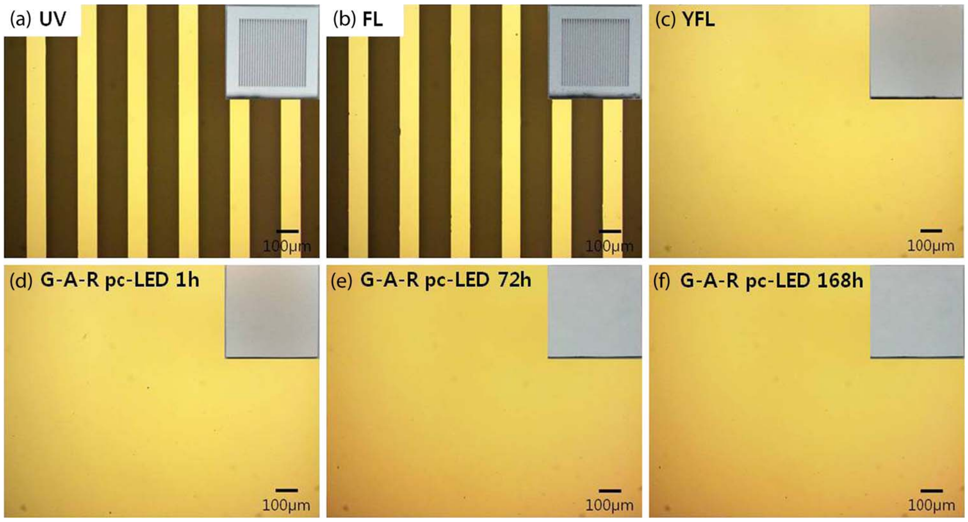

Fig. 5. Optical microscope photographs (insets: photographs) of PR-coated glass after exposure and developing process: The PR-coated glass substrates were exposed to a (a) UV lamp, (b) FT, (c) YFT, (d) G-A-R pc-LED (1 h), (e) G-A-R pc-LED (72 h), and (f) G-A-R pc-LED (168 h).

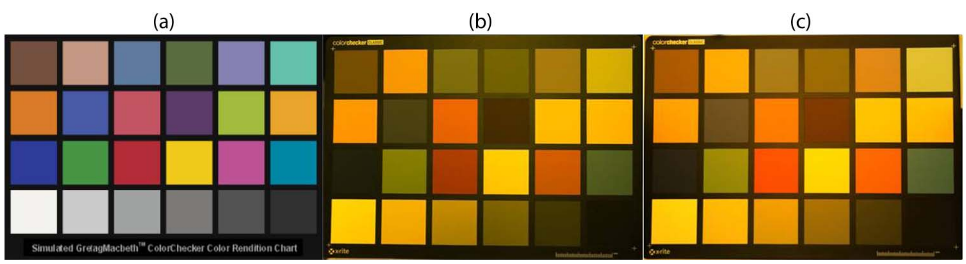

Fig. 6. Color Checker Charts with different lamps using a camera (Canon EOS 6D) with a shutter speed of 1/60 sec, an aperture of F9.0, and the ISO 10 000 condition: The Gretag MacbethTM Color Checker Color Rendition Chart (Xrite Color Checker Chart) under illumination by (a) Color checker chart, (b) YFT, and (c) G-A-R pc-LED lamp at similar CCTs and 1931 CIE color coordinates around 300 lux.

Chart with YFL and the selected G-A-R pc-LED lamp for similar CCTs and 1931 CIE color coordinates, as summarized in Table 2. Both lamps were unable to realize a bluish wavelength because the SPDs of the lamps have no blue emission. The G-A-R pc-LED lamp realizes a purer red color than that of YFL because the G-A-R- pc-LED lamp does have reddish emission.

4. Conclusion

We fabricated nine combinations of multi-package pc-LED lamps by combining LPDF-capped monochromatic G, Y, A, and R pc-LEDs. We optimized the optical properties of the devices to realize a highly efficient, good color-quality yellow-room lamp for use in a photolithographic environment. Among the nine combinations tested, the three-package G-A-R pc-LED was selected as the best candidate for use as a yellow room lamp. This yellow G-A-R pc-LED showed high efficiency (LE = 100 lm/W at 750 mA), good color quality (CRI = 78 and CQS = 36), and wide-band mixed spectrum that covered the wavelengths 490–740 nm. These values are better than those of the YFL (CRI = 38 and CQS = 5) for similar CCT and 1931 CIE color coordinates. We confirmed that the selected G-A-R yellow pc-LED lamp does not initiate a photochemical reaction of PR when PR is exposed to light emitted from the G-A-R pc-LED lamp for 168 h. The good color-quality LED lamp should be helpful to those who work in photolithographic environments by lessening their eye fatigue. These results demonstrate that the use of highly efficient, good color-quality multi-package yellow LEDs that incorporate LPDF-capped monochromatic pc-LEDs can facilitate developments in the specialized LED lighting market.

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