Highly-efficient, tunable green, phosphor-converted LEDs using a long-pass dichroic filter and a series of orthosilicate phosphors for tri-color white LEDs

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Abstract: This study introduces a long-pass dichroic filter (LPDF) on top of a phosphor-converted LED (pc-LED) packing associated with each corresponding tunable orthosilicate ($(Ba,Sr)_2SiO_4$:Eu) phosphor in order to fabricate tunable green pc-LEDs. These LPDF-capped green pc-LEDs provide luminous efficacies between 143–173 lm/W at 60 mA in a wavelength range between 515 and 560 nm. These tunable green pc-LEDs can replace green semiconductor-type III-V LEDs, which present challenges with respect to generating high luminous efficacy. We also introduce the highly-efficient tunable green pc-LEDs into tri-color white LED systems that combine an InGaN blue LED and green/red full down-converted pc-LEDs. The effect of peak wavelength in the tunable green pc-LEDs on the optical properties of a tri-color package white LED is analyzed to determine the proper wavelength of green color for tri-color white LEDs. The tri-color white LED provides excellent luminous efficacy (81.5–109 lm/W) and a good color rendering index (64–87) at 6500 K of correlated color temperature (CCT) with the peak wavelength of green pc-LEDs. The luminous efficacy of the LPDF-capped green monochromatic pc-LED and tri-color package with tunable green pc-LEDs can be increased by improving the external quantum efficiency of blue LEDs and the conversion efficiency of green pc-LEDs.

OCIS codes: (220.0220) Optical design and fabrication; (230.0230) Optical devices; (230.1480) Bragg reflectors; (230.3670) Light-emitting diodes.

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1. Introduction

InGaN-based green light-emitting diodes (LEDs) have suffered from low electroluminescence efficiency compared with blue and red III-V LEDs. This is known as the "green gap" problem, and it impedes the use of efficient green color from semiconductor-type III-V LEDs. Furthermore, InGaN–based green LEDs show poor current dependence compared to InGaN-based blue LEDs. This is well known as the "green droop" problem [1–3]. Over the past decade, many approaches have been taken to address the "green gap" and "droop" problems of green InGaN LEDs [4,5]. However, lower efficacy and droop are still inevitable in green LEDs relative to blue InGaN LEDs.

An alternative means of creating direct electroluminescence of green light is combining highly-efficient blue or near-ultraviolet (n-UV)/violet LED and efficient color conversion materials (an approach known as down-conversion). Previous researchers have suggested four different down-conversion approaches to mitigate the "green gap" and "droop" problems using efficient color conversion materials. Figure 1 schematically summarizes the four different types of green LEDs using color conversion materials.

First, a traditional and facile approach is the simple combination of blue or n-UV/violet LED and green color conversion materials (see Fig. 1(a)) [6]. Kurai et al. reported a luminous efficacy over 110 lm/W at 20mA in a green LED consisting of a violet LED (405 nm) and SrBaEuSiO green phosphors [7]. Recently, Schmidt et al. reported that efficacies as high as 166 lm/W at 350 mA were achieved using a blue LED (434 nm) and $SrSi_2O_2N_2$:Eu phosphors [8]. However, with this technique, the phosphor layer should be thick and highly concentrated in order to block the unabsorbed blue or n-UV emission from the phosphor converted LED (pc-LED). This approach is also hampered by low phosphor conversion efficiency due to the additional scattering and reflection loss associated with the high concentration of micro-sized phosphor content in the paste.

Second, Muller-Mach et al. introduced an innovative color-by-blue LED idea to realize a monochromatic LED using a densely sintered translucent ceramic phosphor (see Fig. 1(b)) [3,9]. The new morphology of sintered ceramic phosphors was utilized to block the transmitted blue LED light from passing through the phosphor layers and reduce the

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scattering loss of powders. However, they only reported the realization of a few pc-LEDs due to limited available colors in the ceramic plate-type phosphors.

Third, Miller et al. suggested a new type of highly-efficient green-emitting color converted LED. Green color-converted LEDs were fabricated by bonding CdMgZnSe multiple quantum well structures to highly-efficient blue LEDs (see Fig. 1(c)) [10,11]. A device efficacy of 181 lm/W, more than twice that of typical commercial green LEDs, was measured at 350 mA. However, relatively sensitive change of dominant wavelength of the narrow green emission band in temperature requires some level of passive and active feedback for white point control. In addition, longevity studies of II-VI quantum well materials are urgently needed to verify that they are sufficiently reliable to meet the expectations of the full LED markets (more than 20,000 hrs).

Fourth, the authors reported on the fabrication of highly efficient monochromatic pc-LEDs using a long-pass dichroic filter (LPDF) and various phosphors to address the problem of the low performance of monochromatic LEDs at various wavelengths in the region of the "green gap", as shown in Fig. 1(d) [12,13]. A modified quarter-wave type of LPDF consisting of a TiO_2/SiO_2 nano-multilayered film was simply capped on top of various phosphor-coated InGaN-based blue LED packages to block and recycle unabsorbed transmitted blue emission. Our simple and facile concept created various kinds of full down-converted color LEDs in the wavelength region of green gap, as there are tremendous kinds of color conversion materials available in today's market.

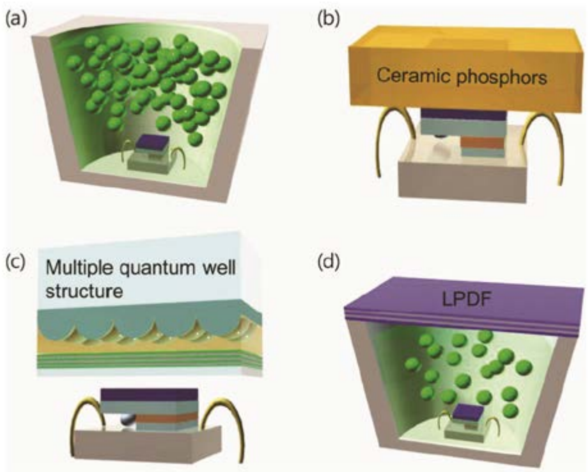

Fig. 1. Schematic diagrams of four different types of full down-converted green LEDs using color conversion materials. Different green pc-LEDs are fabricated using: (a) blue or n-UV/violet LED and a high concentration of phosphors, (b) blue LED and densely sintered translucent ceramic phosphors, (c) blue LED and a CdMgZnSe multiple quantum well structures, (d) blue LED and phosphors capped with a long-pass dichroic filter (LPDF).

For the aforementioned reasons, the development of highly-efficient monochromatic green LEDs is required to achieve balance with blue and red colors of tri-color based LED devices in various applications, such as tri-color or multi-color white LED lamps and full color LED displays [14,15]. Our previous reports on a full down-conversion approach only suggested the possibility of realizing various green LEDs in the peak wavelength of the green gap [12,13]. However, there is little information on the efficiency limit, color tunability, and the detailed optical properties of various LPDF-capped green pc-LEDs. The luminous efficacies and color coordinates of full down-converted green LEDs depend on the combination of three components in the approach of LPDF-capped pc-LEDs, such as blue LED chips, green phosphors, and LPDFs. Here, only one type of LPDF (the band-edge of the long-wavelength = 535 nm) was selected to realize various green LEDs, because the wavelength gaps between blue emission of the InGaN chip and green emissions of phosphors are too narrow to insert various types of LPDFs with band-edge wavelengths. The external efficiency of the blue chips, the phosphor concentration, and the emission wavelength of the green phosphors are thus more important factors to determine the performance and color of LPDF-capped green pc-LEDs. Therefore, this study presents how the luminous efficacies, color coordinates, and current dependence of LPDF-capped green pc-LEDs pumped by a relatively high-efficiency blue chip (external quantum efficiency, EQE = 0.49) are varied with the concentration of a series of green phosphor in paste. We also compare the optical performances of LPDF-capped tunable green pc-LEDs with the red-shift of the peak wavelength in the orthosilicate ($(Ba,Sr)_2SiO_4$:Eu) green phosphor family [16] and compare the results to those of a direct green emitting InGaN LED. Furthermore, we discuss the suitability of the peak wavelength of these tunable green pc-LEDs for application to recently developed, tri-color package white LED lamps that combine a blue LED and full-conversion green/red pc-LEDs.

2. Experimental methods

Fabrication of LPDFs: A dielectric LPDF was fabricated on glass substrates with a thickness of 0.15 mm. For fabrication of the LPDF stacks, terminal eighth-wave thick TiO_2 (t: 25 nm) and quarter-wave thick SiO_2 (t: 73 nm) nano-multilayered films ($(0.5TiO_2/SiO_2/0.5TiO_2)^9$) were coated onto a glass substrate by e-beam evaporation at 250°C [13]. The base pressure in the e-beam chamber was fixed at 4.0 x 10^{-5} torr. The deposition was performed at an acceleration voltage of 7 kV with an oxygen partial pressure of 1.9 x 10^{-4} torr. The refractive indices (n) and extinction coefficients (k) of the e-beam evaporated SiO_2 and TiO_2 films were measured using a spectroscopic ellipsometer (Sentech, SE800). The measured n and k values were used to simulate the reflectance (R), transmittance (T), and absorption (A) in the design of the LPDFs. For the design of the LPDF multilayer film for the blue-excited pc-LEDs, the characteristic matrix method was used to simulate the reflectance (R), transmittance (T), and absorption (A) of the optical structure of the LPDF stacks [13]. In the simulation, the thicknesses of the high-index (TiO_2) and low-index (SiO_2) films were varied in order to tune the spectral position of the reflectance band. In this study, one type of LPDF with nine periods of $0.5TiO_2/SiO_2/0.5TiO_2$ multi-layers (535 nm for green at the band-edge of the long-wavelength) was fabricated as a capping filter to fabricate tunable full down-converted green pc-LEDs.

Fabrication of a series of LPDF-capped green pc-LEDs or a red pc-LED: To fabricate the full down-converted pc-LEDs, a blue chip (λmax = 445 nm) was used simultaneously as a blue light source and an excitation source for various green phosphors and one red phosphor of pc-LEDs. Blue LED chips were purchased from Alti-semiconductor Co. Ltd. A series of tunable $(Sr,Ba)_2SiO_4$:Eu orthosilicate phosphors [16] and a red phosphor ($(Sr,Ca)AlSiN_3$:Eu) [17] were also used as tunable green pc-LEDs or a red pc-LED in this experiment, respectively. A series of tunable orthosilicate green phosphors were selected based on the peak wavelength of green emission (G**5**15: $(Ba_{0.9},Sr_{0.1})_2SiO_4$:Eu, G521: $(Ba_{0.7},Sr_{0.3})_2SiO_4$:Eu, G530: $(Ba_{0.5},Sr_{0.5})_2SiO_4$:Eu, G540: $(Ba_{0.3},Sr_{0.7})_2SiO_4$:Eu, G550: $(Ba_{0.2},Sr_{0.8})_2SiO_4$:Eu, G560: $(Ba_{0.1},Sr_{0.9})_2SiO_4$:Eu; each number is shown with the maximum peak wavelength of the emission spectrum, and the composition is the nominal value). The powder phosphors were obtained from phosphor companies (Merck Co. and Mitsubishi Materials). Optimum amounts of green or red phosphor were dispersed in a silicone binder, and the same amounts of the resulting phosphor pastes were dropped onto a cup-type blue LED to create the tunable green pc-LEDs or a red pc-LED. On top of the tunable green pc-LEDs or a pc-LED, a LPDF-coated glass substrate was attached with an air gap.

Characterization of phosphor powders and monochromatic LEDs: The emission spectra of forward emissions from orthosilicate green phosphors, nitride red phosphor, III-V blue LED, III-V green LED, and blue-excited LPDF-capped monochromatic pc-LEDs were measured in an integrated sphere using a spectrophotometer (PSI Co. Ltd., Darsapro-5000). The luminous efficacy and quantum efficiency were defined as the brightness and the integrated emission spectra of LPDF-assisted pc-LEDs, respectively, at a constant current or

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power. The EQE and color coordinates of the various full down-converted color pc-LEDs were obtained with the current at optimum phosphor concentrations.

Characterization of $R_{B,M}G_{B,M}B$ tri-package white LEDs: A set of primary LEDs with peak wavelengths of 445 nm (blue), 515–560 nm (a series of green), and 625 nm (red) was selected for $R_{B,M}G_{B,M}B$ three-package white LEDs by analyzing the optical properties of $R_{B,M}G_{B,M}B$ three-package white LEDs. Here, $R_{B,M}$ and $G_{B,M}$ are denoted as a LPDF-capped, full down-converted, monochromatic red, and green pc-LED pumped by a blue LED chip. The primary LEDs were put into a triangle lattice fixture for three-package white LEDs under direct current (DC) operation. Each primary LED was controlled separately by an individual power supply for the particular combination of the primary fixtures required for the selected color points. The luminous efficacies, CRIs, and the luminous fluxes from each set of white LEDs were measured in an integrated sphere using a spectrophotometer. The fractional applied currents of the primary LEDs in six different $R_{B,M}G_{B,M}B$ three-package white LED sets with tunable green pc-LEDs were measured to achieve two correlated color temperatures (CCTs: 3500 and 6500 K).

3. Results and discussion

We selected a highly efficient InGaN blue chip (EQE = 0.49, λ_{max} = 445, rated current = 60mA) as an excitation source for the green phosphors in pc-LEDs to compare the luminous efficacy and optical properties of LPDF-capped green pc-LEDs. It is necessary to determine the effects of different peak wavelengths of green phosphors on the optical properties of full down-converted green pc-LEDs and the recently developed multi-package white LEDs created by a simple combination of a blue LED and green/red full-converted pc-LEDs. To this end, we selected an orthosilicate green phosphor family ($(Ba,Sr)_2SiO_4$:Eu) as a series of green phosphors capable of emitting tunable green colors in the wavelength range between bluish green (G515) and yellowish green (G560) [16].

Figures 2(a) and (b) show the relative luminous efficacy and color purities of green pc-LEDs without a LPDF and green pc-LEDs with a LPDF as a function of the phosphor concentration using G550 green phosphor. The capping of the LPDF on top of a series of green pc-LEDs with relatively low phosphor concentrations resulted in somewhat of an increase in the relative luminous efficacy of the forward green emission compared to that of a series of orthosilicate pc-LEDs without a LPDF with a relatively high phosphor concentration at equal-current (60 mA) and at similar 1931 Commission Internationale d'Eclairage (CIE) color coordinates. It is clearly shown that the use of a series of powder-based green pc-LEDs can lead to appropriate color purity at a low phosphor concentration when using the proposed LPDF. The low phosphor concentration of green pc-LED without a LPDF has a relatively high color purity level because the emission spectrum has a higher portion of transmitted blue emission than green emission. It does not show green color purity but blue color purity when the phosphor concentration is very low. In the case of the green pc-LED with a LPDF, the appropriate concentration of each pc-LED is about 30wt% while for a green pc-LED without a LPDF, the appropriate concentration is higher than 60wt% to obtain the maximum level of luminous efficacy for good color purity of each tunable green phosphor. Figure 2(c) shows the luminous efficacy of selected green pc-LEDs with and without a LPDF showing 1931 CIE color coordinates similar to the corresponding powder phosphor as a function of the peak wavelength of a tunable green pc-LED. As the wavelength of the green pc-LED increases, an increased gap of the luminous efficacy can observed between the green pc-LEDs with and without a LPDF owing to the decreased overlapping of the reflectance spectrum of the LPDF and the green phosphor spectrum. One explanation for this is that the bluish green phosphor has more of an overlapped spectrum with the LPDF compared to the yellowish green phosphor. When the larger portion of the emission spectrum of the green pc-LED overlaps the LPDF reflectance spectrum, the luminous efficacy becomes lower. For this reason, the luminous efficacy levels of the bluish green pc-LEDs (G515) with and without a LPDF are quite similar. However, the luminous efficacy levels of yellowish green pc-LEDs (G550,

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G560) are improved by about ~17% with a LPDF at a similar color purity level and the 1931 CIE color coordinates.

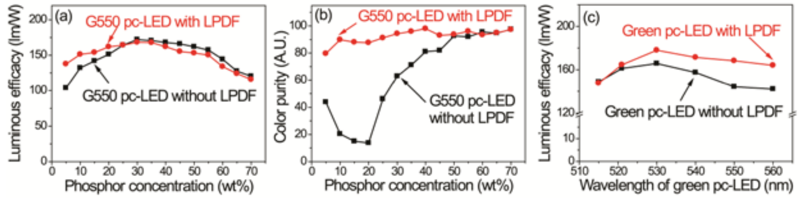

Fig. 2. (a) The relative luminous efficacies and (b) color purity of green pc-LEDs with and without a LPDF as a function of the phosphor concentration using G550 green phosphor in paste. (c) The luminous efficacy of selected green pc-LEDs with and without a LPDF with similar 1931 CIE color coordinates to the corresponding phosphor as a function of the peak wavelength of a tunable green pc-LED. All measurements were performed under equal-current conditions (60 mA).

Figures 3(a) and (b) show the photoluminescence (PL) spectra and color coordinates of a series of orthosilicate green phosphors excited by blue light. Although they are not the best green phosphor candidates for this purpose, they are well-known tunable phosphors for application to tunable green pc-LEDs. This figure also shows that increasing the Sr composition in $(Ba_{1-x},Sr_x)_2SiO_4$:Eu phosphors causes red shift behavior in the PL peak, as previously reported [16].

This redshift behavior can be interpreted in terms of the increased crystal field strength with increasing Sr^{2+} ions in $(Ba_{1-x},Sr_x)_2SiO_4$:Eu. Therefore, the Ba:Sr ratio can be simply controlled in order to obtain the desired green emission wavelength of $(Ba_{1-x},Sr_x)_2SiO_4$:Eu orthosilicate phosphors in the wavelength range of the green gap. As above mentioned with respect to the optimization process in a series of orthosilicate powder phosphor pastes [13], the concentration of the phosphor pastes in each green LPDF-capped pc-LED was carefully selected to guarantee the maximum level of luminous efficacy and color purity similar to that

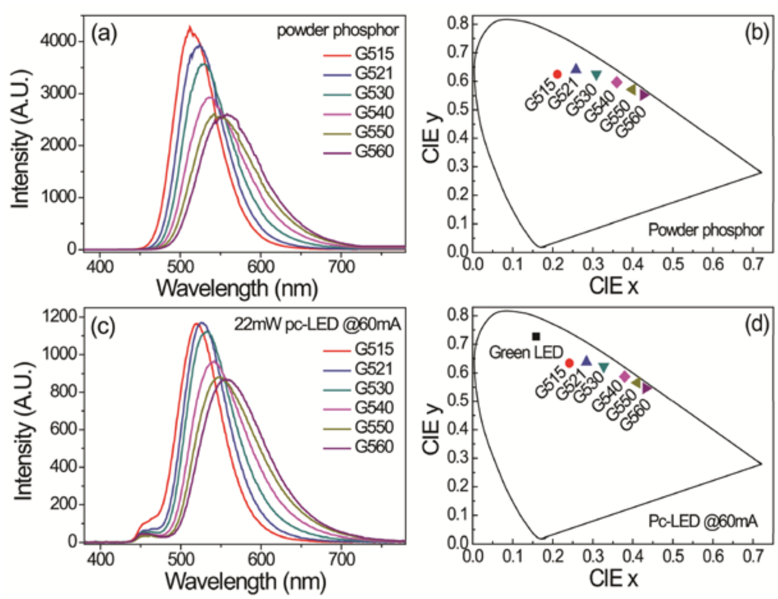

Fig. 3. (a) Photoluminescence spectra and (b) Color coordinates of a series of orthosilicate green phosphors excited by blue light. (c) Electroluminescence spectra and (d) color coordinates of six different LPDF-capped green pc-LEDs associated with corresponding green phosphors.

of the corresponding phosphor. The EL spectra and color coordinates of six different green colors of LPDF-capped pc-LEDs with optimum phosphor concentrations are shown in Figs. 3(c) and (d). The EL spectra clearly show that there are very few peaks observed in the blue region of each spectrum of all full down-converted green LEDs due to the blocking and recycling of the pumping blue light by a capped LPDF. It is clearly confirmed that pure green color can be simply obtained by depositing any kind of green powder phosphors over a blue chip in the LPDF-capped pc-LEDs.

The peak maximum EL wavelengths and color coordinates from six green LPDF-capped pc-LEDs nearly coincide with those from six powder phosphors under excitation at 445 nm. A variety of pure green colors in the wavelength range of the green gap can be obtained by varying the composition of green $(Ba,Sr)_2SiO_4$:Eu phosphor materials in the LPDF-capped pc-LEDs. These similarities between phosphors and pc-LEDs in terms of CIE color coordinates also confirm that the LPDF-capped pc-LEDs can reproduce any tunable green colors from a series of green phosphor from bluish green to yellowish green in the chromaticity diagram. Therefore, the full down-conversion phosphor technology provides similar versatility to semiconductor technology in terms of tailoring the wavelength of primary green emitters.

Figures 4(a)–(f) show the luminous efficacy, luminous flux, and color coordinates of conventional InGaN green LED and six tunable LPDF-capped green pc-LEDs as functions of applied current and ambient temperature. With the exception of the green pc-LED incorporated with G515 phosphors, five full down-converted green pc-LEDs have reduced or at least similar variations of the efficacy, luminous flux, and color coordinates with current/temperature relative to the wide variation in the levels of current/temperature stability of conventional semiconductor-type green InGaN LEDs that do not contain phosphors.

The G515 phosphor-based green pc-LEDs show slightly worse current and temperature dependence of luminous efficacy and flux than the corresponding green pc-LEDs. As expected, this is mainly due to the relatively low quantum efficiency and fast temperature quenching phenomenon of PL of the G515 green phosphor compared to the other green phosphors used in this experiment. Although there are some variations of efficacy, luminous flux, and color with current and temperature, a variety of highly efficient green pc-LEDs using a long-pass dichroic filter (LPDF) and a series of orthosilicate phosphors can address the problem of the low performance of III-V LEDs at various wavelengths in the region of the "green gap."

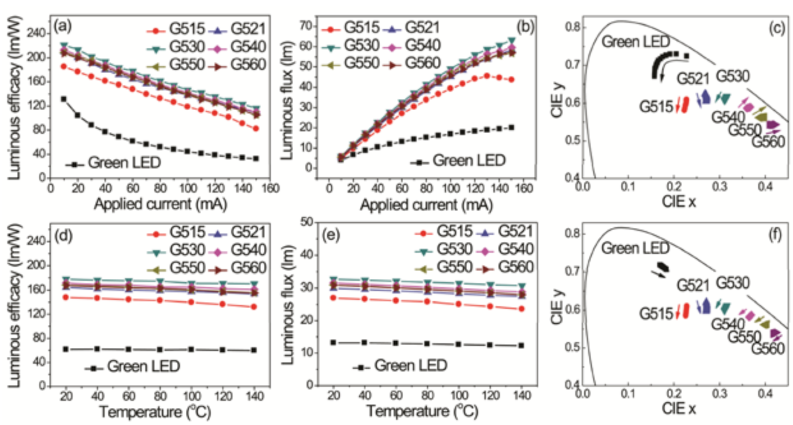

Fig. 4. (a) Luminous efficacy, (b) Luminous flux, and (c) Color coordinates of conventional InGaN green LED and six tunable LPDF-capped green pc-LEDs as functions of applied current (arrow indicates the increase of current). (d) Luminous efficacy, (e) Luminous flux, and (f) Color coordinates of conventional InGaN green LED and six tunable LPDF-capped green pc-LEDs as functions of ambient temperature (arrow indicates the increase of temperature).

Figure 5(a) displays the measured luminous efficacy at 60 mA and the luminous efficiency of the radiation (LER) of six tunable green LPDF-capped pc-LEDs. As is well known, the LER, in lumen per watt, is a parameter explaining how bright the radiation of the emission spectrum is perceived by the average human eye [18]. Individual LER is the maximum value of lm/W obtained in each green emission spectrum of the above-mentioned pc-LEDs with tunable green phosphors. It is necessary to consider the Stokes shift between the emission spectrum of each green phosphor and the excitation spectrum of the blue LED; energy losses are estimated to be 13.6–19.6%, and thus we can calculate the maximum luminous efficacies of green lights in the present six LPDF-capped pc-LEDs with the peak wavelength of the green phosphors.

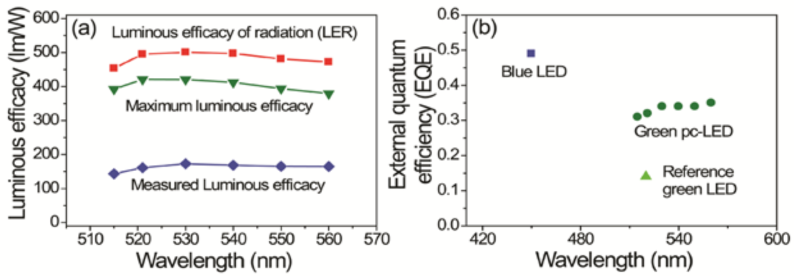

Fig. 5. (a) The measured luminous efficacy at 60 mA and the luminous efficiency of the radiation (LER) of six tunable green pc-LEDs. (b) EQE values for a blue (B0.49), a green III-V LED and a family of tunable green pc-LEDs.

The maximum luminous efficacies (η_{lm}) of the LPDF-capped pc-LEDs are shown in Fig. 5(a). The measured luminous efficacies (η_{lm-m}) are about 143–173 lm/W (143, 161, 173, 169, 165, and 165 lm/W for each pc-LED), which are roughly 0.37–0.43 of the theoretical maximum values. Furthermore, the ratio of the measured luminous efficacy (η_{lm-m}) to the luminous efficiency of the radiation (LER) gives the external quantum efficiency (EQE, η_{e-pc}) of our engineered green pc-LED samples, on the basis of the following equation:

$$\eta_{e-pc} = \eta_{lm-m} / LER = \eta_e \times \eta_{con} = \eta_e \times (\eta_p \times \eta_{pkg}) \tag{1}$$

It is simply assumed that the EQE (η_{e-pc}) of full down-conversion LPDF-capped pc-LED is equal to the product of the EQE (η_e) of the blue pumped LED and the conversion efficiency (η_{con}) of a LPDF-capped pc-LED, which is equal to the internal quantum efficiency (η_p) of phosphor times the packaging efficiency (η_{pkg}) of a LPDF-capped pc-LED. Figure 5(b) shows the EQE values for the blue and green III-V LED used in this paper and a family of tunable green LPDF-capped pc-LEDs. As aforementioned, we used an efficient blue LED having an EQE (η_e) of 0.49 to convert EL color from blue to green in this study. The conversion efficiencies (η_{con}) of six green LPDF-capped pc-LEDs are measured as 0.64, 0.66, 0.70, 0.69, 0.70, and 0.71 for each full down-conversion pc-LED. If we plug both η_e = 0.49 and η_{con} = 0.64–0.71 in Eq. (1), the EQE of our green pc-LED samples is calculated to fall in a range of 0.31–0.35. These EQE values are in good agreement with the values calculated from the ratio of the measured luminous efficacies (143–173 lm/W) to the luminous efficiencies of the radiation (LER) (454–501 lm/W). If we use the best blue LED with the theoretically high EQE value of 0.7 and the best LED package with a conversion efficiency of 0.9 in the near future, the expected EQE and measured luminous efficacies in the LPDF-capped green LEDs are estimated to be about ~0.63 and 286–315 lm/W, respectively, with the peak wavelength of green pc-LEDs. Moreover, these expected EQEs of LPDF-capped green

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pc-LEDs based on a blue LED are higher than those estimated from green pc-LEDs fabricated by using UV or a violet LED, as shown in Fig. 1(a). The enhanced possibility of achieving higher EQEs of this LPDF-capped green-by-blue pc-LED sample is due to the reduced energy loss by Stokes shift and the enhanced recycling ability of reflected blue light by LPDF compared to a green-by-UV/violet pc-LED with a high concentration of phosphor. Therefore, it is shown that our LPDF-capped full-conversion pc-LED technique can provide the possibility of increasing luminous efficacy with improvement of the EQE in a blue InGaN LED up to 286 ~315 lm/W with an increase of peak wavelength of green pc-LEDs from 515 to 560 nm. For the time being, the LPDF-capped green pc-LED can cover wavelength of 510–570 nm, which is difficult to achieve with a InGaN green LED, before a highly-efficient semiconductor-type green LED is developed in the future.

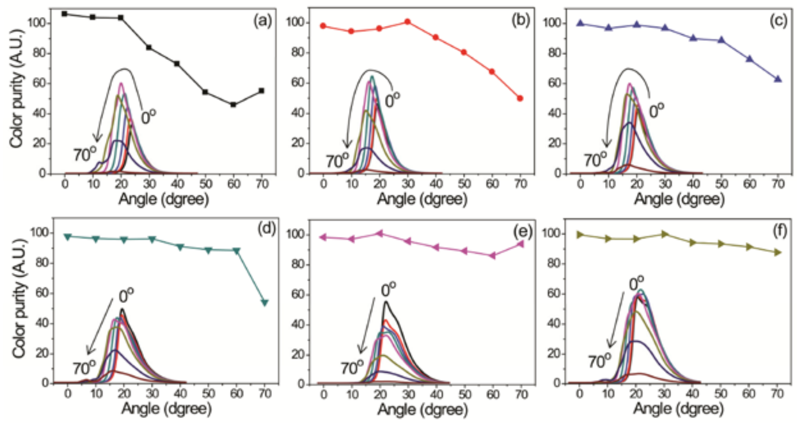

Fig. 6. The color purity and emission spectra of each green pc-LED with a LPDF as a function of the viewing angle: (a) G515, (b) G521, (c) G530, (d) G540, (e) G550, (f) G560.

Similar to the incident angular dependence of the reflected wavelength and the polarization of conventional ODR filters, our modified quarter-wave stacks of LPDFs are also characterized by the angle dependence of the reflected color. Furthermore, because the reflection band area of our LPDF involves the emission spectrum range of the green phosphor, the measured emission spectra of the LPDF-capped pc-LED in the normal direction were distorted. However, to ensure high color purity in green LEDs, LPDFs of a wide band range are necessary because they have to block and recycle any unabsorbed blue LED light. Figure 6 shows the color purities and emission spectra of each green pc-LED as a function of the viewing angle. As shown in Figs. 6(a)–(f), the color purity and emission spectra were affected by the viewing angle. These effects caused by the angular dependence were well observed in bluish green phosphors, which are close to blue LED emission. As shown in Figs. 6(a) and Fig. 6(f), the emission spectra of the bluish green pc-LED with a LPDF (Fig. 6(a), which is close to the blue wavelength) were distorted more strongly compared to the yellowish green pc-LED with a LPDF (Fig. 6(f)). However, white light is obtained from the spatial mixing and redistribution of the light emitted from each pc-LED and blue LED in our multi-package white LEDs. Therefore, the angular dependence of the color and polarization of LPDFs in the normal direction are likely an inconsequential issue given that the white light is obtained from the mixed light of a multi-package LEDs. Moreover, as shown Figs. 3(a) and 3(c), the green pc-LEDs with a LPDF give an emission spectra nearly identical to that of the powder phosphor spectra in the measurement system of an integrated sphere.

Quiet recently, we demonstrated a facile and new $R_{B,M}G_{B,M}B$ tri-color white-light approach that combines a blue LED and green/red full-conversion monochromatic pc-LEDs to enhance the performance of white light, reduce the variation in the temperature/current/time dependence of each colored LED, enhance the color rendering of white light, and dynamically control the color points [19]. $R_{B,M}$ and $G_{B,M}$ respectively denote

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LPDF-capped, full down-converted, monochromatic red and green pc-LED pumped by an efficient blue LED chip. Here, we studied the effect of six tunable green colors of LPDF-capped pc-LEDs on the performance, color rendering index, and optical properties of tri-color package white LEDs.

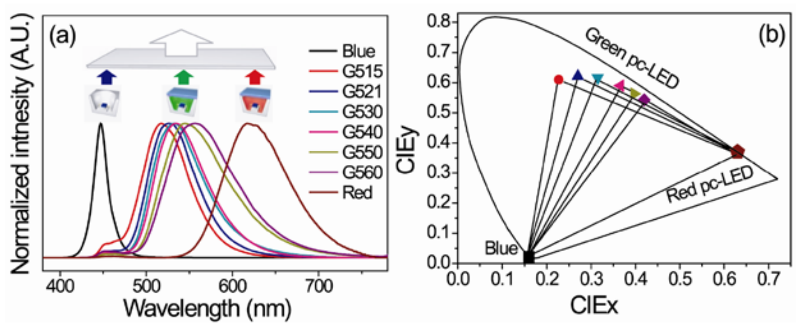

Fig. 7. (a) Normalized EL emission spectra and (b) Commission Internationale d'Eclairage (CIE) color coordinates of a blue LED, $(Sr,Ca)AlSiN_3$:Eu red pc-LED, and six tunable $(Ba,Sr)_2SiO_4$:Eu) green pc-LEDs.

Figure 7(a) shows the normalized emission spectra of blue LED, $(Sr,Ca)AlSiN_3$:Eu pc-LED, and six tunable $(Ba,Sr)_2SiO_4$:Eu green pc-LEDs. A set of primary LEDs with peak wavelengths of 445 nm (blue), six tunable greens, and 625 nm (red) was selected for the $R_{B,M}G_{B,M}B$ tri-package white LEDs by analyzing the effect of varying the peak wavelength of a green pc-LED on the optical properties of the $R_{B,M}G_{B,M}B$ tri-package white LEDs. Figure 7(b) shows the color diagram of the 1931 CIE color coordinates of each white-light system with an increase of the peak wavelength of tunable green pc-LEDs. The color reproduction area (color gamut) of the $R_{B,M}G_{B,M}B$ tri-package white LEDs is decreased with an increase of the peak wavelength of the green pc-LED, because the color coordinates of the green pc-LED shift to reddish color with an increase of peak wavelength.

Figures 8(a) and (b) show the overlapped integrated emission spectra of each LED in a $R_{B,M}G_{B,M}B$ tri-package white-light for 6500 and 3500 K correlated color temperatures (CCTs) along with the peak wavelength of six tunable green pc-LEDs. The fractional applied current of the primary LEDs in each $R_{B,M}G_{B,M}B$ tri-package white light is gradually changed with a red-shift of the peak wavelength of the LPDF-capped green pc-LED (see Figs. 8(c) and (d)). These figures indicate that the fractional intensity and current of the green pc-LED are increased by an increase of peak wavelength of the LPDF-capped green pc-LED in the $R_{B,M}G_{B,M}B$ white LED system. Any specified white colors and all colors in the triangle area in the CIE diagram can be realized by dynamically controlling the fractional applied current in the full-conversion pc-LED tri-package white LEDs.

As is well known, the meaningful figures of merit in white light applications are the luminous efficacy and color rendering index (CRI, Ra) of the white light at the same color point. Figures 9(a) and (b) compare the luminous efficacy and color rendering index of $R_{B,M}G_{B,M}B$ tri-package white-light at 6500 and 3500 K as a function of the peak wavelength of the tunable green pc-LED. They were measured under a constant total applied current (180 mA) with a specified fractional current of each colored LED. At a CCT value of 6500 K, the green portion of the white color increased with an increase of peak wavelength of the green pc-LED and the blue and red portions crossed over at 550 nm. As a result, the luminous efficacy of the $R_{B,M}G_{B,M}B$ reached the maximum value at 550 nm for the green emitting pc-LED. On the other hand, the green portion of the white color increased but the red portion of the white color decreased with an increase of the green emitting wavelength at a CCT of 3500 K. The luminous efficacy of the $R_{B,M}G_{B,M}B$ hence increased monotonously with an increase of emitting wavelength of the green pc-LED.

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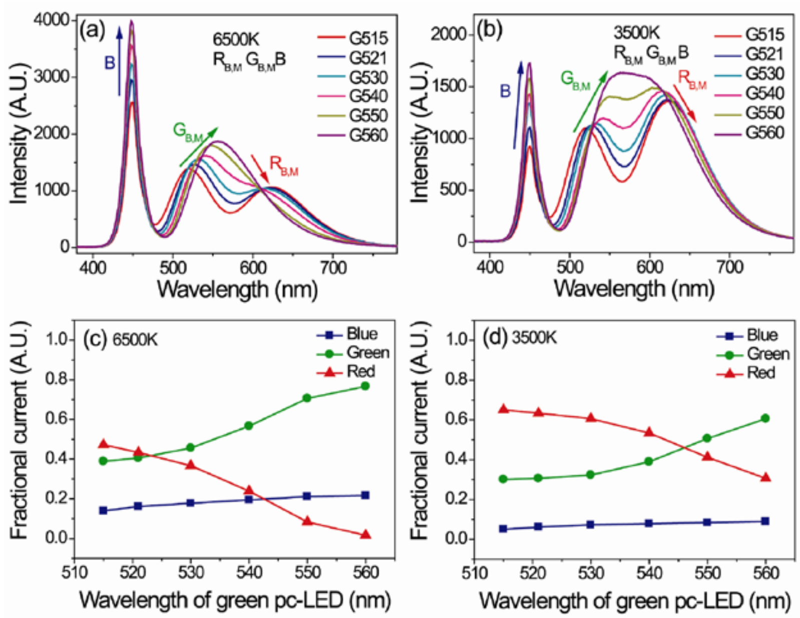

Fig. 8. The overlapped integrated emission spectra of each LED in a $R_{B,M}G_{B,M}B$ three-package white-light along with the peak wavelength of the tunable green pc-LEDs at (a) 6500 and (b) 3500 K. The fractional applied current of the primary LEDs in each $R_{B,M}G_{B,M}B$ three-package white light along with the peak wavelength of the tunable green pc-LEDs at (c) 6500 and (d) 3500 K..

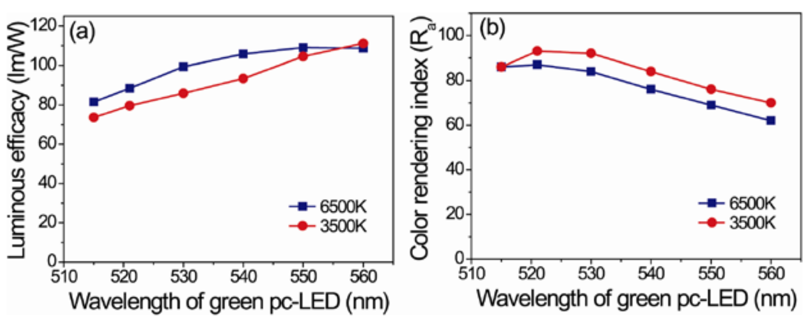

Fig. 9. (a) Luminous efficacy and (b) color rendering index of $R_{B,M}G_{B,M}B$ three-package white-light at 6500 and 3500 K as a function of the peak wavelength of a tunable green pc-LED.

In contrast with the trend of luminous efficacy, the color rendering index of the $R_{B,M}G_{B,M}B$ white-light was slightly raised to 521 nm and then slowly decreased with an increase of emitting wavelength of the green pc-LED at either a CCT of 6500 or 3500 K. These figures simply indicate that both luminous efficacy and color rendering index are in a trade-off relationship in this $R_{B,M}G_{B,M}B$ white-light system with peak wavelength of the green pc-LED. These figures also indicate that it is difficult to select the peak wavelength of green pc-LEDs for attaining both high luminous efficacy and color rendering index in the $R_{B,M}G_{B,M}B$ white-light system. For example, if we select 530 nm pc-LED, $R_{B,M}G_{B,M}B$ tri-package white-light provides high luminous efficacies (99 and 86 lm/W) and moderate color rendering index (84, 92) at 6,500 and 3,500 K CCT. From the perspective of efficacy, the 560 nm green pc-LED shows the best luminous efficacies for the $R_{B,M}G_{B,M}B$ white-light system: 108 and 111 lm/W at 6500 and 3500 K, respectively. On the other hand, from the perspective of CRI, the 521 nm green pc-LED provides the best CRI values for the $R_{B,M}G_{B,M}B$ white-light

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system: 87 and 91 at 6500 and 3500 K, respectively. Therefore, in order to improve and optimize both luminous efficacy and color rendering index simultaneously, it is necessary to optimize the number, peak wavelength, and bandwidth of the primary LPDF-capped pc-LED as well as the radiative fluxes for each combination of the newly developed multi-package white-light approach in our lab, which combines a blue LED and more than two full down-conversion colored pc-LEDs.

4. Conclusions

The concept of monochromatic LPDF-capped pc-LEDs recently developed in our lab can be applied to develop highly-efficient tunable green LEDs in the wavelength ranges of the green gap of semiconductor-type LEDs by using a series of orthosilicate ($(Ba,Sr)_2SiO_4$:Eu) green powder phosphors. We have demonstrated that the luminous efficacy of tunable LPDF-capped green pc-LEDs reaches 143–173 lm/W in the wavelength range between 515 and 560 nm at 60 mA, respectively. We have also suggested that the EQE and luminous efficacies of the LPDF-capped green LEDs can be increased by improving the EQE of the blue LED and the conversion efficiency of our engineering pc-LED to ~0.63 and 286–315 lm/W, respectively, with the peak wavelength of green pc-LEDs. The highly-efficient green pc-LEDs can be exploited in the recently developed $R_{B,M}G_{B,M}B$ tri-color white-light approach, which combines a blue LED and green/red full-conversion monochromatic pc-LEDs to enhance the performance and optical properties of white light. We have also shown that the luminous efficacies and CRIs of $R_{B,M}G_{B,M}B$ tri-color white-light with a 530nm LPDF-capped green LED are 99/86 lm/W and 84/92 at 6,500 and 3,500 K CCT, which are higher than the corresponding values of conventional semiconductor RGB tri-color LEDs. Moving beyond these performances of green pc-LEDs and newly-developed $R_{B,M}G_{B,M}B$ tri-color white LEDs will require further optimization of the LPDFs and phosphors, particularly the conversion efficiency of LPDF-capped LEDs in each color region, as well as improvements in the EQE of the blue LED.

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