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Design of white tandem organic light-emitting diodes for full-color microdisplay with high current efficiency and high color gamut

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Abstract

Microdisplays based on organic light-emitting diodes (OLEDs) have a small form factor, and this can be a great advantage when applied to augmented reality and virtual reality devices. In addition, a high-resolution microdisplay of 3000 ppi or more can be achieved when applying a white OLED structure and a color filter. However, low luminance is the weakness of an OLED-based microdisplay as compared with other microdisplay technologies. By applying a tandem structure consisting of two separate emission layers, the efficiency of the OLED device is increased, and higher luminance can be achieved. The efficiency and white spectrum of the OLED device are affected by the position of the emitting layer in the tandem structure and calculated via optical simulation. Each white OLED device with optimized efficiency is fabricated according to the position of the emitting layer, and red, green, and blue spectrum and efficiency are confirmed after passing through color filters. The optimized white OLED device with color filters reaches 97.8% of the National Television Standards Committee standard.

KEYWORDS

color gamut, microdisplay, organic light-emitting diode, tandem OLED, white OLED

1 | INTRODUCTION

In a social climate that reduces contact between people, augmented reality (AR) and virtual reality (VR) devices have attracted considerable attention as an important hardware technology [1–3]. A microdisplay is an integral part of AR and VR devices. Organic light-emitting diodes (OLEDs), liquid crystal on silicon (LCoS), and micro-light-emitting diodes (LEDs) are all potential candidates for use in a microdisplay. Because OLED microdisplays have a smaller form factor and faster response times than LCoS, their use in AR and VR devices is advantageous as portability and low latency are important requirements [1]. Micro-LEDs are not yet technically mature; thus, it is possible to preemptively apply OLED technology, which is already mass-produced to television (TV) and mobile displays, to microdisplays [4,5]. In the early days, one disadvantage of OLEDs was their lower resolution as compared with that of LCoS. However, a high-resolution microdisplay of 3000 ppi or more has been reported using a white OLED structure and a color filter patterned by photolithography [6].

Compared with other microdisplays, a further weakness of the OLED-based microdisplay is that of low luminance. High luminance is an important requirement for AR devices used in outdoor or indoor lighting. For OLED-based microdisplays to become mainstream technology, it is important to overcome the problem of low luminance. To improve luminance, there is a method for directly patterning the red/green/blue (RGB)-emitting layer instead of applying a color filter to the white OLED [7]. However, it is difficult to create high resolution by patterning RGB with a shadow mask. Although it is possible to improve the luminance by introducing a microlens array outside the OLED device [8], it is important to proactively increase the luminance of the device itself.

The OLED device should have a top-emitting structure as the microdisplay is fabricated on a silicon substrate [9,10]. In a top-emitting structure, a thin metal layer is generally applied as a top electrode. Compared with transparent electrodes, such as indium tin oxide and indium zinc oxide (IZO), a thin metal layer has a relatively strong cavity effect owing to its high reflectivity, and this is a disadvantage for obtaining a broad white spectrum. In addition, unlike monochrome OLEDs, the effect of improving efficiency in white OLEDs is not significant. A study in which IZO was applied as a top electrode in an OLED-based microdisplay has been reported, but sputtering deposition and a suitable electron injection layer for the IZO were also required [8].

By applying a tandem structure in an OLED device, as is already applied in OLED TV applications, the current efficiency can be improved without introducing a new process. A tandem-structured OLED has a superior lifetime and driving as well as better color stability compared with a single white OLED in which the primary colors, namely, red, green, and blue, are mixed in one emitting layer [11–13]. However, unlike conventional OLED displays, as the OLED-based microdisplay is driven by a complementary metal–oxide–semiconductor (CMOS) circuit formed on a silicon wafer, the driving voltage is limited. Fortunately, our research group confirmed that OLEDs with a two-stack tandem structure can be driven by a CMOS circuit and demonstrated a white OLED-based microdisplay [14]. When designing an OLED structure for a white OLED-based microdisplay, the intensity of the yellow–green emission was intentionally lowered to match that of the blue emission to achieve a white color coordinate. However, in a full-color OLED-based microdisplay, primary colors are obtained by white spectrum from the OLED device passing through color filters. Therefore, it is advantageous to change the OLED structure to have a white spectrum that can obtain high efficiency and high color gamut according to the characteristics of the color filter. In this study, a tandem OLED structure was designed to be suitable for a full-color microdisplay, and a color filter was applied to a fabricated white OLED device to confirm the color gamut.

2 | OPTICAL SIMULATION

For optical simulation, the commercial software SETFOS (Fluxim) was used. The optical constants of organic materials, such as a hole transporting layer (HTL), an emission layer (EML), and an electron transporting layer (ETL), were measured via spectroscopy (Figure S1), and those of Ag and Al were borrowed from the literature [15] and the software. The photoluminescence (PL) spectra of a blue fluorescent material and a yellow–green phosphorescent material are presented in Figure S2. It is assumed that the internal quantum efficiency is 100%, and an emission zone is placed in the center of an EML.

When designing a tandem OLED structure, the thickness of the total organic layer (t_{tot}) between the bottom reflective electrode and the top transparent electrode is first determined. Figure 1 presents the relative luminance of an OLED device having only a blue or yellow–green light-emitting layer according to the thickness of the ETL (t_{ETL}) and the HTL (t_{HTL}), respectively. Luminance significantly fluctuates as both the t_{ETL} and t_{HTL} change. As a result, the t_{tot}, the sum of t_{ETL}, t_{HTL}, and EML thickness (20 nm), should be considered first. The optimized t_{tot} for blue and yellow–green emission is 215 nm and 275 nm, respectively. The resonance conditions of blue fluorescence with a peak emission wavelength of 455 nm and yellow–green phosphorescence with a peak emission wavelength of 550 nm cannot be satisfied simultaneously. Therefore, the t_{tot} is negotiated to be thicker than the blue optimized thickness and thinner than the greenish-yellow optimized thickness. It is reasonable to determine the final thickness to be 245 nm (red dashed diagonal line, Figure 1).

After determining the t_{tot} in the tandem structure, the position of the blue and yellow–green emitting layers is then considered as well as the thickness of the common organic layers of each EML. Depending on the position of the EML, there are two possible structures: (1) a blue EML is deposited first followed by a yellow–green EML (BYG–OLED), and (2) conversely, the yellow–green EML is deposited first followed by a blue EML (YGB–OLED); see Figure 2A. Then, to optimize the efficiency of each structure, the thickness of the common organic layers is determined: these include a charge generation layer and the HTLs and ETLs of each EML. Figure 2B shows that

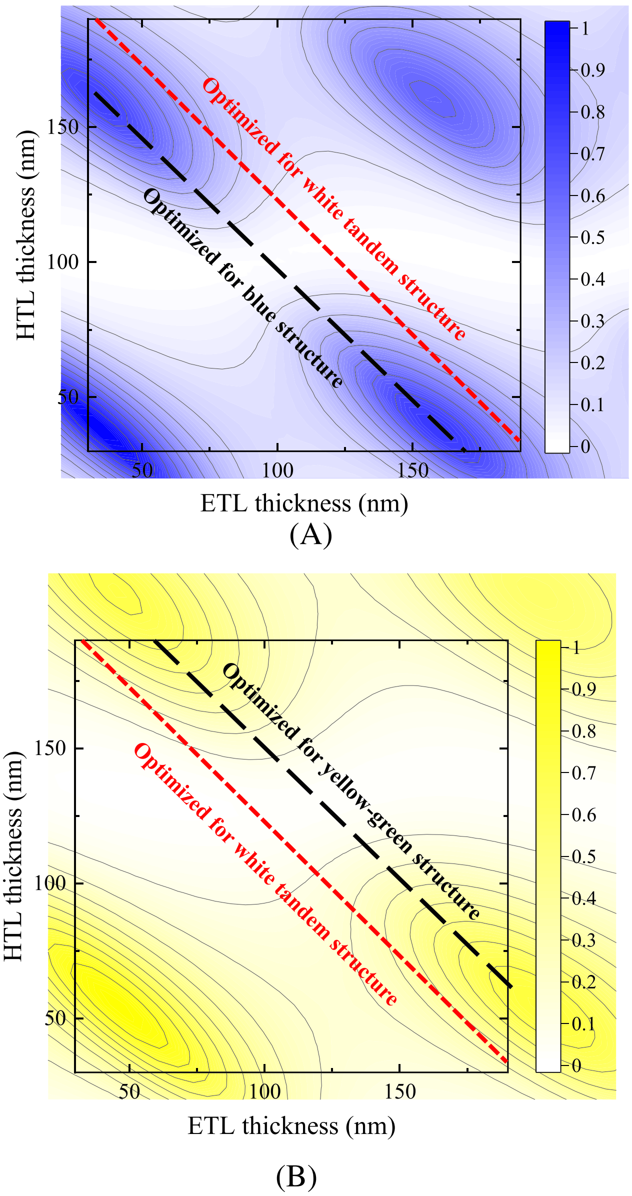

FIGURE 1 Relative luminance according to the thickness of the hole transporting layer (HTL) and the electron transporting layer (ETL): (A) blue fluorescence and (B) yellow–green phosphorescence

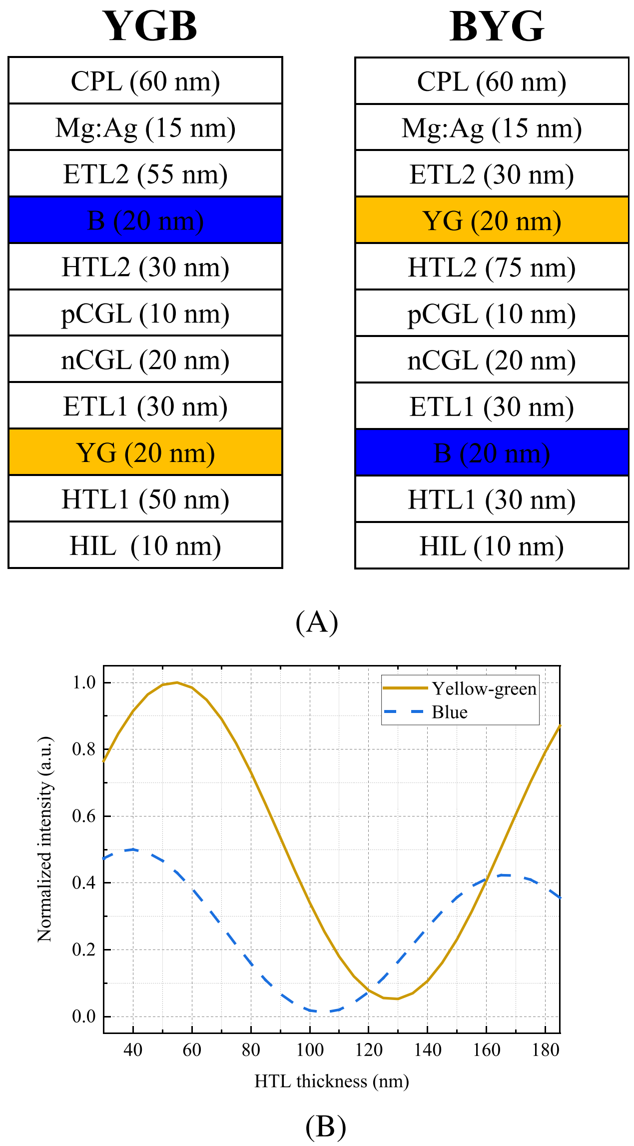

FIGURE 2 (A) Tandem organic light-emitting diode structure depend on the position of the emission layer. (B) Normalized intensity of blue and yellow–green emission according to the thickness of the hole transporting layer (HTL) when the total thickness of the organic layers is fixed at 245 nm

the normalized intensity emitted by the blue and yellow–green EML was calculated by changing the t_{HTL} when the t_{tot} was fixed at 245 nm. Because blue emission is fluorescent, its intensity was normalized to half the intensity of the green–yellow emission. Because the t_{tot} is thicker than the thickness-optimized blue emission, there are two optimized t_{HTL}: 40 nm in a BYG structure and 170 nm in a YGB structure. However, because t_{tot} is thinner than the thickness-optimized yellow–green emission, there is only one optimized t_{HTL}: 55 nm in a YGB structure. Therefore, the optimized t_{HTL} for yellow–green emission in a BYG structure is determined by considering that for electrical stability, the minimum thickness of the t_{ETL} is 30 nm. Based on the simulation results, the thicknesses of each layer in the YGB and BYG structures for fabricated OLED devices are presented in Figure 2A.

3 | EXPERIMENTS

3.1 | OLED device fabrication

OLED devices were fabricated on test element group (TEG) Si wafer substrates. As TEG substrates were fabricated in a commercial foundry, the 8-inch wafer was diced to a substrate size suitable for OLED evaluation. A photoresist covered the wafer substrates to protect the surface while dicing an 8-inch wafer to a 20 mm × 20 mm size. After removing the photoresist, the diced substrates were sequentially cleaned with acetone and deionized water and then transferred to a vacuum thermal evaporator. Because the Al/TiN anodes were already patterned on the TEG wafer, organic materials and Mg/Ag (1:10) cathode metals (Taewon Scientific Co.) were deposited with the structure and thickness presented in Figure 2A. The fabricated OLED devices were encapsulated using ultraviolet (UV) light-curing epoxy resins (Nagase ChemteX Corporation) in an N_2-filled glove box.

3.2 | Color filter and OLED device characterization

Two kinds of color filters, Kodak Wratten filters (CF-K) and mounted color filters (CF-H), were purchased from Edmond Optics. A PerkinElmer Lambda 750 UV/Vis/NIR spectrophotometer was used to measure the color filter transmittance. Both the electrical (current density [*J*] and voltage [*V*]) and optical (luminance [*L*] and electroluminescence [EL] spectra) properties of the OLED devices were measured using a Keithley 238 source meter and a Konica Minolta CS-2000 spectroradiometer.

4 | RESULTS AND DISCUSSION

4.1 | Color filter characteristics

Figure 3A presents images of the blue, green, and red filters of the CF-K and CF-H. When viewed with the naked eye, there is no significant difference between the blue and red filters, but the green filter of the CF-K appears more vivid than that of the CF-H. This can be confirmed from the transmittance measurement of the color filters as presented in Figure 3B. Both blue filters have a similar cut-off wavelength and maximum transmittance. There is a region in which the transmittance of the CF-H blue filter is slightly increased by approximately 1.5% at a wavelength of 560 nm. This is presented in the inset of Figure 3B, where the wavelength range of 510 nm to 590 nm is magnified. The red filters differ in transmittance by between 5% and 10%. In addition, the cut-off wavelength of the red filter transmittance of the CF-H is longer than that of the CF-K, but the transmittance does not decrease rapidly at wavelengths below 580 nm, as presented in the inset of Figure 3B. The green filters of the CF-K and CF-H have similar maximum

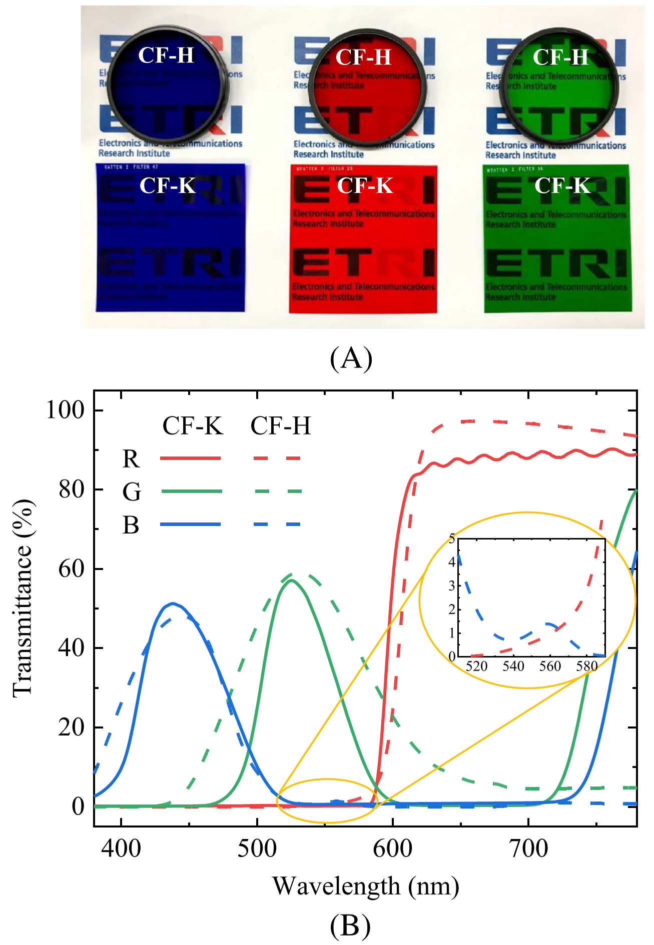

FIGURE 3 (A) Images and (B) transmittance of the blue, green, and red filters of the Kodak Wratten filter (CF-K) and the mounted color filter (CF-H) series

transmittance, but the bandwidth of the transmittance is significantly different. When combined with OLED devices, these differences influence the impact on the color coordinates, as will be discussed in detail later.

4.2 | White OLED device characteristics

Figure 4A presents the current density–voltage–luminance (*J-V-L*) characteristics of tandem OLEDs with a YGB and BYG structure. Both devices exhibit turn-on voltage as low as 5.2 V, where *L* is 1 cd/m^2, and *L* of over 10 000 cd/m^2 at 8 V. Both devices have similar electrical properties as only the position of the EML and the thicknesses of the common organic layers differ: The materials of the common organic layers are all the same. However, the optical properties differ significantly. As presented in Figure 4B, the current efficiency of the YGB–OLED is much greater than that of the BYG–OLED. As mentioned in the simulation section, the yellow–green emission is

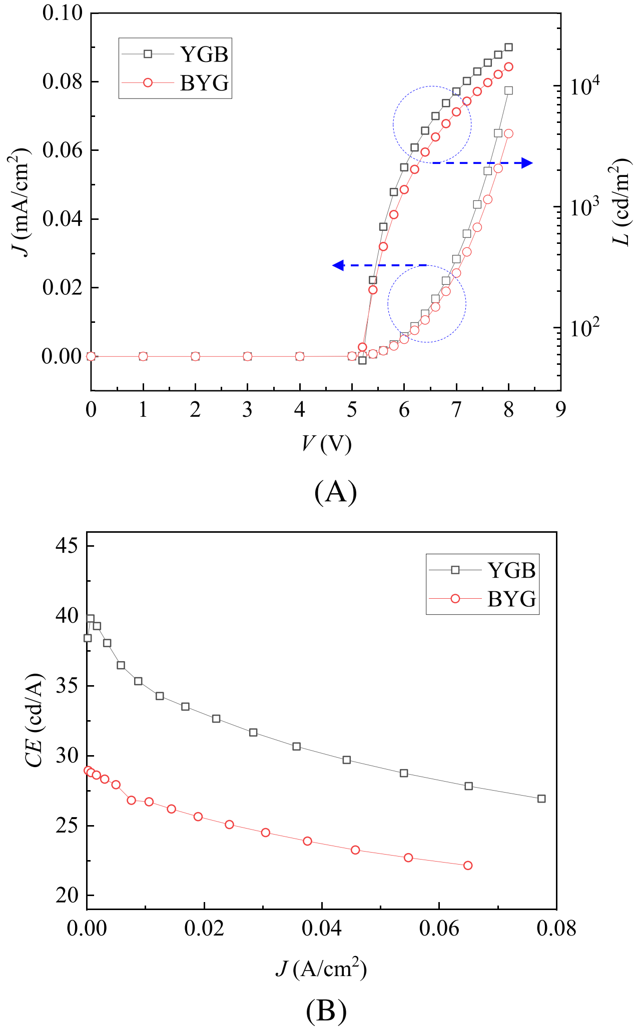

FIGURE 4 (A) Current density–voltage–luminance (J-V-L) curve and (B) current efficiency (CE)–J curve of the tandem OLED with a YGB and BYG structure

optimized only in the YGB–OLED. As a result, the intensity of the yellow–green emission in the tandem BYG–OLED is 87% of that of the YGB–OLED. In the case of blue emission, the BYG–OLED has a 7% greater intensity than the YGB–OLED. However, the effect of this difference in intensity on blue emission is minor in current efficiency as blue light is emitted from a fluorescent material and luminance is mainly determined by the yellow–green emission. Therefore, the YGB–OLED is more advantageous for high efficiency.

4.3 | OLED device with color filter characteristics

To identify the optimal structure to achieve high color gamut, red, green, and blue emission spectra were measured by combining two color filters with each tandem OLED. Figure 5A presents the normalized EL spectra of both the YGB–OLED and BYG–OLED. At the same current density of 5 mA/cm^2, the BYG–OLED had a similar blue and yellow–green emission intensity, whereas the YGB–OLED demonstrated a yellow–green emission intensity greater than the blue emission intensity. This is because the BYG–OLED is better optimized for blue emission, whereas the YGB–OLED is better optimized for yellow–green emission, as described above. In addition to the difference in intensity, the bandwidth of the emission spectrum is also different. The "full width at half maximum" of the emission spectrum in the YGB–OLED is 134 nm, whereas that in the BYG–OLED is 125 nm, and the latter originates mainly from the yellow–green emission. The EL spectrum (I_{out}) is described by the products of two factors: the Fabry–Pérot (f_{FP}) factor and the two-beam interference (f_T) factor as follows [16]:

$$I_{out} = f_{FP} \times f_T \times I_0, \tag{1}$$

with

$$f_{FP} = \frac{T_{top}}{\left(1-\sqrt{R_{top}R_{bot}}\right)^2 + 4\sqrt{R_{top}R_{bot}}\sin^2\left(\frac{\Delta\phi}{2}\right)}, \tag{2}$$

$$f_T = 1 + R_{bot} + 2\sqrt{R_{bot}}\,\cos\left(-\phi_{bot} + \frac{4\pi nz}{\lambda}\right), \tag{3}$$

where I_0 denotes the PL spectrum; T_{top} is the transmittance through the Mg/Ag top electrode from the organic layer; and R_{top} and R_{bot} are the reflectance at organic/top electrode and organic/bottom electrode interfaces, respectively. $\Delta\phi$ denotes the phase term given by

$$\Delta\phi = -\phi_{top} - \phi_{bot} + \frac{4\pi nd}{\lambda}, \tag{4}$$

where ϕ_{top} and ϕ_{bot} denote the phase changes occurring upon reflections at the organic/top electrode and organic/bottom electrode interfaces, respectively, and n and d denote the refractive index and the thickness of the total organic layer, respectively. z in 3 is the location of the emission zone measured from the organic/bottom electrode interface. Considered from the viewpoint of the yellow–green EML, the T_{top}, R_{top}, and R_{bot} in 2 are the same because the organic materials and the electrode in both OLED structures are the same. Also, d in 4 is the same as in the simulation section, in which the total thickness of the OLED devices was first determined. The only difference is z in 3, which is the first- and second-order cavity lengths in the YGB–OLED (60 nm) and

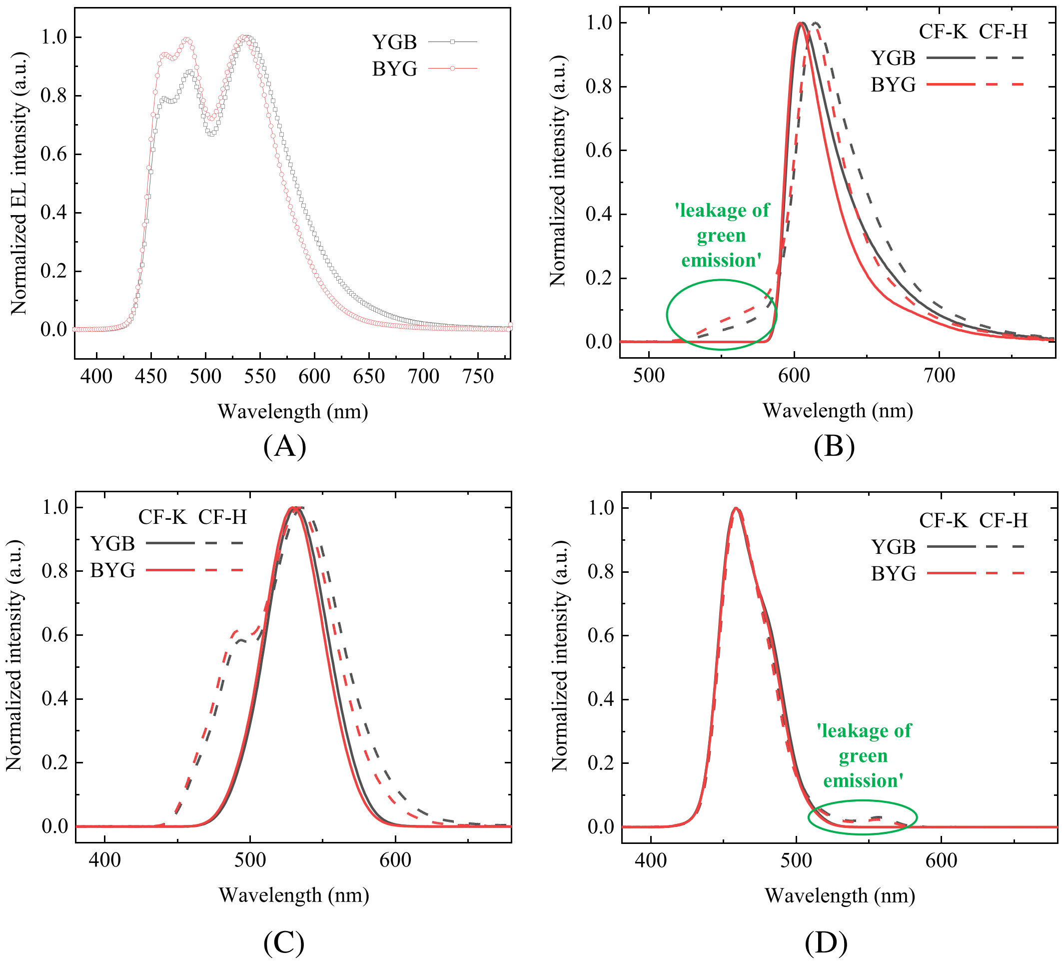

FIGURE 5 (A) Normalized electroluminescence (EL) spectra of tandem organic light-emitting diodes with a YGB and BYG structure. The normalized EL spectra passing through (B) red, (C) green, and (D) blue Kodak Wratten filters (CF-K) and mounted color filters (CF-H)

BYG–OLED (185 nm), respectively. As the position of the EML moves away from the bottom electrode, the f_T spectrum narrows [16]. Therefore, the yellow–green emission spectrum of the BYG–OLED is narrower than that of the YGB–OLED. This result is also confirmed by the simulation, as presented in Figure S3.

Figure 5B presents the normalized emission spectra passing through red filters. The emission spectra are different as the transmittance characteristics of each color filter and the white emission spectra of each OLED structure are reflected. For red emission, OLEDs with the CF-H have a longer peak emission wavelength than those with the CF-K, but there is a little green emission. The color coordinates of the YGB–OLED are (0.662, 0.337) and (0.653, 0.346) for the CF-K and CF-H, respectively. When the CF-K is applied, a more saturated red can be obtained. Depending on the OLED structure, as described above, it can be seen that the red emission is broader in the YGB–OLED, where the yellow–green emission was broad. For the same color filter, the YGB–OLED has a color closer to the saturated color. For example, with the CF-H, the color coordinates are (0.653, 0.346) and (0.634, 0.365) for the YGB and BYG structures, respectively.

For the green emission, because the bandwidth of the color filter transmittance is reflected, the bandwidth of the green emission spectrum passing through the color filters is significantly different, as presented in Figure 5C. The narrower the bandwidth of the color filter transmittance, the closer the emission spectrum passing through the color filter to the saturated color. The YGB–OLED has color coordinates of (0.225, 0.701) and (0.259, 0.567) for the CF-K and CF-H, respectively. Figure 5D presents the normalized emission spectra passing through blue filters. As in the transmittance of the color filters, the green emission appears in the CF-K, but it does not significantly affect the color coordinates. The color coordinates according to the device structure and the type of color filter are summarized in Figure 6. The inset in Figure 6 is the emission image of the YGB–OLED with the CF-K. According to the red, green, and blue color coordinates

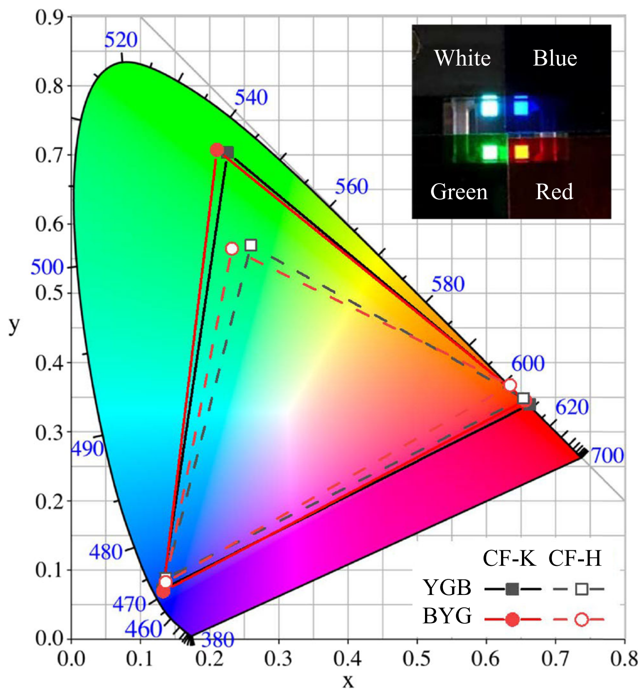

FIGURE 6 The color coordinates according to the device structure and the type of color filter, Kodak Wratten filter (CF-K) and mounted color filter (CF-H). Reproduced from Wikipedia, CC BY-SA 3.0, https://upload.wikimedia.org/wikipedia/commons/thumb/0/02/CIExy1931.svg/1024px-CIExy1931.svg.png

for the OLED structure and the type of color filter, the color gamut based on the national television standards committee (NTSC) standard is presented in Table 1. The transmittance of color filters predominantly determines the color gamut rather than the OLED structures. When the CF-K is applied, color gamut of 97.8% and 98.7% of the NTSC standard can be achieved in the YGB–OLED and BYG–OLED, respectively.

In addition to color, the luminance of OLEDs passing through the color filters is also important. As the current efficiency is different depending on the OLED structure, relative luminance is compared and summarized in Table 1. Blue and red each account for less than 5% of relative luminance. In other words, to achieve sufficient luminance in blue or red, white is driven very brightly.

For the same color filter, the BYG–OLED has a higher blue proportion than the YGB–OLED as it is optimized for blue emission but not for yellow–green emission. For red emission, the YGB–OLED has a broad white emission, as presented in Figure 5A. As a result, the red emission is also broad, as presented in Figure 5B, and has a higher red proportion than the BYG–OLED. Owing to the broad white emission, the YGB–OLED has a smaller green proportion. However, the luminance value at the same current density is much higher in the YGB–OLED

TABLE 1 Color gamut and relative luminance of organic light-emitting diodes (OLEDs) according to the device structure and the type of color filter, Kodak Wratten filter (CF-K) and mounted color filter (CF-H)

		Color gamut[a] (%)		Relative luminance[b] (%)	
		CF-K	CF-H	CF-K	CF-H
YGB	Red	97.8	68.4	5.4	4.5
	Green			32.6	46.5
	Blue			2.4	2.9
BYG	Red	98.7	67.2	3.1	2.7
	Green			34.6	47.9
	Blue			3.2	3.5

[a]Ratio based on the National Television Standards Committee standard.
[b]Luminance after passing through color filters/luminance of white OLEDs (1778.8 cd/m^2 for YGB and 1337.9 cd/m^2 for BYG).

than the BYG–OLED, as shown in Figure 4B. This means that the luminance of the green emission is much greater in the YGB–OLED where the yellow–green emission is optimized. As a result, in terms of luminance or efficiency, the YGB–OLED, which minimizes loss in blue light emission and optimizes emission of both the green and red light, is suitable for full-color display.

Depending on the type of color filter, the relative luminance of the green emission differs the most. This difference originates from the transmittance of the color filter. The CF-H with a wide bandwidth and can increase luminance by passing more green light, but there is a tradeoff relationship in which color purity is lowered due to the wideness of the bandwidth of the green emission. The higher luminance of the CF-H in blue resulted in green emission leakage. This means that the green emission is not completely removed through the CF-H and therefore leaks a little, as presented in Figure 5D. In red, the CF-H also demonstrated leakage of green emission, as shown in Figure 5B. However, because its peak wavelength is longer, the luminance is rather low. As a result, the OLED white spectrum first includes all three primary colors corresponding to red, green, and blue with optimized efficiency. In red and blue filters, leakage should be minimized, and the cut-off wavelength suitable for the white OLED spectrum should be determined. In green filters, the bandwidth of the transmittance is reduced, and peak transmittance is increased.

5 | CONCLUSION

In summary, this optical study presented the design for a two-stack tandem white OLED structure for use in a full-color microdisplay. The tandem structure was used to overcome low luminance, one of the disadvantages of an OLED microdisplay. Owing to the limitation of driving the voltage by the CMOS circuit, the tandem structure should consist of two EMLs, namely, blue and yellow–green. By using an optical simulation, two structures with optimized efficiency were determined according to the position of EML. One involved depositing the blue first followed by the yellow–green. In the other, the yellow–green was deposited first followed by the blue. After being combined with a color filter, the transmittance of the color filter determined the color gamut. Therefore, it was desirable to first design a white OLED structure to optimize efficiency and have a wide spectrum and then to apply a color filter with greater efficiency and high color gamut in accordance with the OLED spectrum. OLED devices were fabricated based on the simulation, and their optical characteristics were confirmed. OLED devices where yellow–green was deposited first exhibited greater efficiency. When color filters are applied to the OLEDs designed for efficiency optimization, color gamut of 98.7% of the NTSC standard can be achieved.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR CONTRIBUTION

Hyunsu Cho designed the study, contributed to the simulation and experiment, and wrote the manuscript. Chul Woong Joo and Sukyung Choi contributed to the experiment and the discussion. Chan-mo Kang, Byoung-Hwa Kwon, and Hyunkoo Lee contributed to the design of OLED devices. Gi Heon Kim and Jin Wook Shin contributed to the discussion about color filters. Chun-Won Byun and Nam Sung Cho contributed to the discussion and background of this study. All authors commented on the manuscript draft and approved the submission.

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SUPPORTING INFORMATION

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