High Brightness OLED Lighting

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Abstract
In this work we describe the technology developments behind our current and future generations of high brightness OLED lighting panels. We have developed white and amber OLEDs with excellent performance based on the stacking approach. Current products achieve 40-60 lm/W, while future developments focus on achieving 80 lm/W or higher.

Author Keywords
OLED; lighting; high brightness; stacked; efficacy; CRI; amber

1. Objective and Background
OLED lighting holds great promise as a new form of solid-state lighting that produces naturally diffuse and pleasant light in a very thin form factor. In order to fulfill its full promise, performance must be continually improved and cost must be steadily reduced. OLED lighting panels are typically thought of as low brightness tiles that can be pieced together to create beautiful and artistic luminaires with new form factors. Most commercially-available OLED lighting panels output under 100 lumens each, or under 1 lm/cm^2. In order to produce luminaires with an appreciable amount of light for general lighting applications, many of these OLED tiles are required and therefore the overall cost is prohibitively high. It is important to enable higher brightness OLED panels which can reduce the cost per lumen, and allow OLEDs to start to penetrate into functional and general lighting applications.

In 2014, Philips launched the Brite FL300 OLED panel which was designed to produce a maximum brightness of 300 lumens. After the acquisition of the Philips OLED lighting business by OLEDWorks in 2015, the rectangular Brite FL300L product was launched, also producing 300 lumens. To the best of our knowledge, these are still the highest brightness and longest lifetime OLED lighting panels available on the market today, enabling entry into general lighting applications that demand higher lumen output. With an emitting area of just over 100 cm^2, the panels operate at a luminance of over 8,000 cd/m^2 in order to produce 300 lumens, or 3 lm/cm^2. Such high lumen output was made possible by developing stacked white OLED structures with thermally stable OLED materials and charge generation layers, along with a solid-state thin film encapsulation system. In 2016, higher performance versions of the Brite OLED panels will be released with improved CRI of 90 and higher efficacy up to 60 lm/W. A high efficiency 50-60 lm/W amber OLED lighting panel will also be introduced in 2016, also based on the stacking approach. We will describe the OLED technology that has enabled these high brightness white and amber OLED panels. We will also review progress on development of next generation higher performance OLED lighting technology.

2. Results
The first generation Brite1 OLED panels incorporate a 6-stack white OLED structure as depicted in Figure 1.

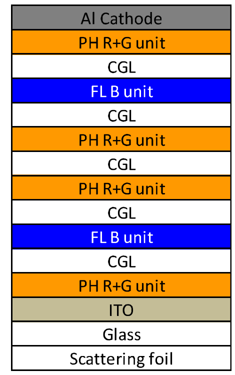

Figure 1. Brite1 white OLED stack

The device is constructed of 4 phosphorescent units and 2 fluorescent blue units, and uses state of the art OLED materials. The phosphorescent units consist of a single emission layer containing both red and green dopants. Each unit contains hole and electron injection, transport, and blocking layers (not shown). In between each unit is a charge generation layer (CGL) that is optimized to provide superior thermal stability. Devices were characterized at accelerated conditions on a hotplate from 50C to 90C in order to control the junction temperature. The luminance decay and voltage increase over time were monitored. Poor-performing CGLs exhibit a breakdown and show a rapid voltage rise when subjected to high temperatures, while optimized CGLs can maintain 1-2V rise over time even at high temperatures.

The higher-order stacking allows the device to achieve high brightness at a modest current density, and therefore we can achieve long lifetime even at high brightness [1]. The reasons for this can be better understood by examining the J-V-L (current-voltage-luminance) relationships.

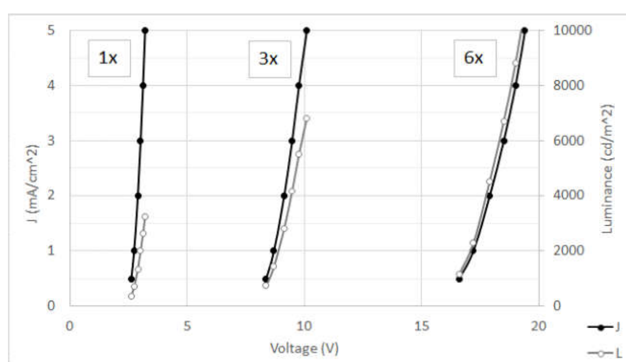

Figure 2: J-V-L curves for 1X, 3X and 6X OLEDs

Figure 2 shows the J-V-L curves for a 1-stack R-G device (1X), a 3-stack white (3X), and a 6-stack white (6X). If we compare the devices at a current density (J) of 2 mA/cm^2, the voltages are 3V, 9V, and 18V for 1X, 3X, and 6X respectively, which are exact multiples of 3 and 6 times the voltage of the 1X device. However, the luminance (L) is quite different. Also at 2 mA/cm^2, the luminance is 1350, 2820, and 4530 cd/m^2 for 1X, 3X, and 6X respectively. These are less than multiples of 3 and 6, since the white devices have a blue stack which contributes very little to the luminance, but of course is necessary to generate white light. A 1X blue device has a luminance of less than 300 cd/m^2 at the same current density.

If we compare the current density necessary to achieve brightness levels of 3,000 and 8,000 cd/m^2 as shown in Table 1, we can see the advantage of the 6-stack device. The 3X device can achieve long lifetime at 3,000 nits (J=2.1), but will have an unacceptable lifetime at 8,000 nits (J=6). The 6X device can still achieve an L70 of 10,000 hours even at high brightness, since the current density is still at a reasonable level of 3.5 mA/cm^2. The 6X device also achieves a very long lifetime of 50,000 hours at 3,000 nits (J=1.3).

Table 1: Current density requirement for standard brightness (3000 nits) and high brightness (8000 nits)

Brightness L (cd/m^2)	1X J (mA/cm^2)	3X J (mA/cm^2)	6X J (mA/cm^2)
3,000	4.6	2.1	1.3
8,000	14	6	3.5

The EL spectra for the same 1X, 3X, and 6X devices are shown in Figure 3.

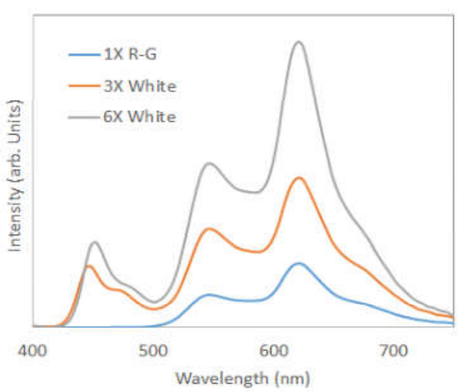

Figure 3: EL spectra for 1X, 3X, and 6X OLEDs

The stacking approach also enables good brightness uniformity over a large area, even without the use of supplementary metal grids. The Brite1 FL300 panel achieves > 90% uniformity (min/max). This is also due to the lower current requirement which reduces the effect of the anode lateral resistance. The higher vertical resistance of the 6X OLED stack results in a lower slope for the J-V-L curves, therefore the same change in voltage will produce a smaller change in brightness. The thin film encapsulation system with a metal foil allows for more effective heat spreading and heat removal from the OLED device, which also has a positive impact on the uniformity.

CRI Improvement

In order to meet the requirement for high quality lighting applications where color rendition is important, the white OLED stack was modified to increase the CRI to 90 and the R9 value to above 50. Compared to the Brite1 white OLED stack (A), the next version white OLED stack (B) employs an improved set of emitters with distinct blue, green, and red peaks. A comparison of the EL spectra is shown in Figure 4.

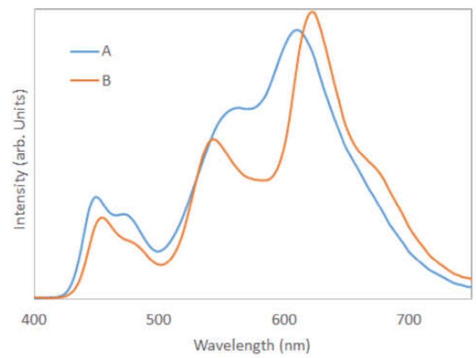

Figure 4: Spectral comparison for standard white stack (A) and improved CRI white stack (B)

CRI is improved from 80 to 90 mainly due to the longer wavelength red peak and shorter wavelength green peak. An R9 of greater than 50 is the result of the improved deep red emission. Still, higher efficacy could be obtained with narrower band deep red emitters, which would increase the LER similar to what LEDs have achieved.

Efficacy Improvement

In addition to higher CRI, higher efficacy is also required to expand into OLED lighting market opportunities which demand higher energy efficiency.

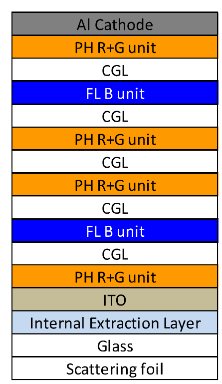

Figure 5: Brite2 white OLED stack

To that end we have been developing OLEDs with improved light outcoupling using internal light extraction technology. The Brite2 OLED panel uses the improved white stack B as well as an internal extraction layer (IEL) as shown in Figure 5. Keeping with aluminum cathode, we are able to achieve 60 lm/W efficacy for this panel. The spectral comparison for the 6X white on standard ITO substrate and IEL substrate is shown in Figure 6. Both have an external outcoupling foil. Due to the higher efficiency for the IEL substrate, the current required to achieve 300 lumens is reduced from 368mA to 260mA, and power is reduced from 7.4W to 5.2W. This is expected to have a positive impact on lifetime and reliability, both of which are still being evaluated. Note that the blue peak emission can experience less outcoupling than the green and red peaks, due to absorption and optical effects. This can cause a CCT shift, which may require tuning of the OLED stack and even compromises in efficacy in order to maintain the same specified CCT.

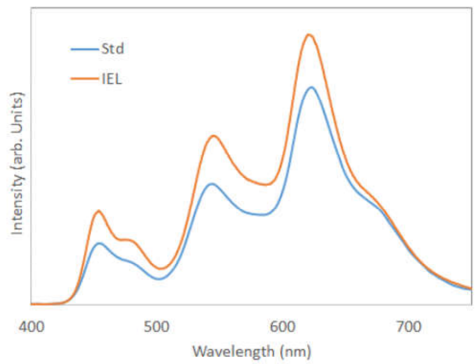

Figure 6: Spectral comparison for 6X white on standard and IEL substrates

White OLED lighting panels with power efficacy of 100 lm/W or greater have been reported [2-5]. Although these are laboratory demonstrations not yet available in commercial product, this demonstrates the potential performance that future OLED lighting panels can achieve. We have been developing higher efficacy white OLEDs based on a highly reflective silver (Ag) cathode, in combination with internal light extraction. We also tested the impact of plasmon decoupling by increasing the thickness of the electron transport layers closest to the Ag cathode. The white device structures used in these evaluations are shown in Figure 7.

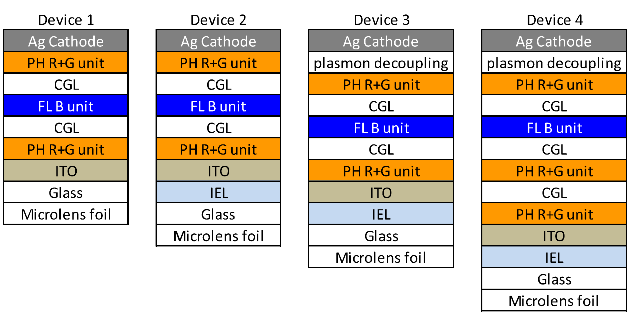

Figure 7: Experimental 3X and 4X white OLED stacks

With just Ag cathode (Device 1), we can achieve close to 60 lm/W at 3,000 nits. The efficacy further improves to 80 lm/W with the combination of Ag cathode and IEL (Device 2). Devices 3 and 4 use a slightly different set of emitters, as well as a plasmon decoupling layer [6].

Table 2: Performance for experimental OLEDs

Device	# stacks	IEL	V	cd/A	EQE	lm/W	CIEx	CIEy
1	3X	no	8.6	155	76	57	0.454	0.403
2	3X	yes	8.6	220	98	81	0.456	0.434
3	3X	yes	8.7	260	114	94	0.451	0.416
4	4X	yes	11.3	360	159	100	0.471	0.433

Device 3 reaches 94 lm/W at 3,000 nits. With an additional phosphorescent stack, Device 4 reaches 100 lm/W at 3,000 nits, although it should be noted that the color point is shifted more warmly. Table 2 shows a summary of the performance for the experimental devices from Fig.7 at 3000 nits. The external quantum efficiency (EQE) is expressed as the ratio of photons outcoupled divided by the electrons passing through the device. The EQE value can reach greater than 100% since it is normally reported as an additive figure in the case of stacked OLEDs. In the case of the 4X device, the overall EQE is 159%, or approximately 40% per stack.

A summary of current performance and predicted future generation white OLED performance is shown in Table 3. The trend is toward higher efficacy without sacrificing color quality. As efficacy increases, the current density requirement is also reduced, translating to longer lifetime. The efficacy is always lower at high brightness since the voltage is higher, but this droop effect is minimized through the use of higher order stacking [6]. As outcoupling efficiency improves with internal extraction and Ag cathode, the CCT can become warmer since blue light is generally not outcoupled as efficiently as green and red. More efficient blue emitters and lower absorption materials are required to combat this effect. After efficacy improves to 90lm/W or greater, it should be practical to achieve high brightness with fewer stacks, and still maintain good lifetime.

Table 3: Technology roadmap for current and future generation white OLED lighting panels

						3000 nits (115 lm)		8300 nits (300 lm)	
Gen	# stacks	IEL	Cathode	CRI	CCT	lm/W	L70 (kh)	lm/W	L70 (kh)
Brite1	6X	no	Al	80	3000K	45	50	42	10
Brite1.5	6X	no	Al	90	3000K	45	50	42	10
Brite2	6X	yes	Al	90	3000K	63	>50	60	>10
future	6X	yes	Ag	90	3000K	84	>50	80	>10
future	3X	yes	Ag	90	3000K	90	50	82	10

High Efficiency Amber OLEDs

We have also developed highly efficient amber OLEDs based on the stacking approach. The lack of UV or blue emission makes amber OLEDs attractive for lighting applications which require minimum disruption to the human circadian system. Applications can range from healthcare and other nighttime lighting applications [7] to lighting of UV-sensitive items. Because the target applications for amber OLEDs do not usually require high brightness, fewer number of stacks can be used.

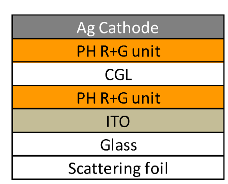

Figure 8: High-efficiency 2X amber OLED

The amber device structure uses a 2-stack approach with Ag cathode, as shown in Figure 8. Since a blue stack is not required, the amber efficacy can be much higher than for white, however this depends on the color. With an external scattering foil at $2mA/cm^2$, a 1X green OLED achieves 130 lm/W (125 cd/A @ 3V), while a 1X red OLED has much lower efficacy of 35 lm/W (33 cd/A @ 3V). The amber unit is a combination of phosphorescent green and red emitters, so the efficacy ends up somewhere in between. If we aim for saturated amber LED color specifications (x~0.56, y~0.43), we can achieve an efficacy of 60 lm/W. Typical device performance with an external scattering film at 2000 nits (2 mA/cm^2) is shown in Table 4.

Table 4: Performance of 2X high-efficiency amber OLEDs

V	cd/A	lm/W	CIEx	CIEx	EQE
5.8	110	60	0.563	0.431	58

The efficacy ranges from 65 lm/W at a low brightness of 500 nits to 53 lm/W at a high brightness of 5000 nits. Efficacy as a function of luminance is shown in Figure 9.

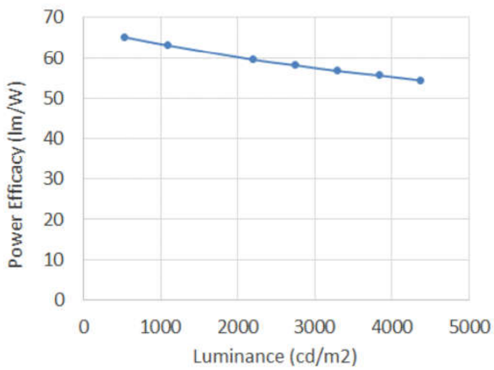

Figure 9: Efficacy vs. luminance for 2X amber OLEDs

The amber color and EL spectrum (inset) can be seen in the chromaticity plots in Figure 10. The amber color varies only slightly over an order of magnitude change in brightness from 500 to 5000 nits. The color remains within the SAE amber color bin as well as a typical amber LED color bin (Philips Lumileds Luxeon Rebel PC Amber).

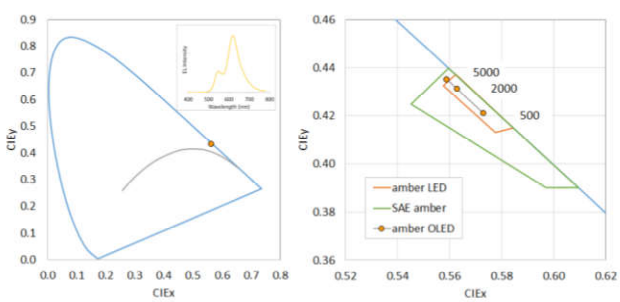

Figure 10: Color and EL spectrum for 2X amber OLEDs

Electrical aging of the devices was carried out at an accelerated condition of 10 mA/cm^2 (11000 nits). With an acceleration factor of 1.5, the extrapolated LT70 at 2 mA/cm^2 (2000 nits) is predicted to be more than 50,000 h.

Future Directions

In order for OLEDs to achieve 100 lm/W in a manufacturable product, improvements on several fronts are required. There is still much room to improve the extraction efficiency of OLEDs through improved internal light extraction materials and other light outcoupling technologies that reduce losses associated with surface plasmons. Although examples of high efficacy white OLEDs up to 140 lm/W have been reported, there is still a need for better outcoupling technology that is both practical and manufacturable. Improved OLED materials are required, especially more efficient and stable deep blue emitters as well as single-material (as opposed to mixed) low-voltage electron transporters. For stacked OLEDs, lower absorption CGLs and transparent conductors are required. At some point outcoupling efficiency and OLED materials technology will improve to the point where the number of OLED stacks can be reduced again to 3X or fewer. Until then, higher order stacking is the most effective approach to achieve high brightness OLED lighting.

3. Impact

This is the first joint publication from the OLEDWorks group and former Philips OLED lighting group (now OLEDWorks GmbH) discussing high brightness white OLED panels that produce 300 lumens (3 lm/cm^2). This work describes the technology necessary to realize OLED lighting panels with higher lumen output, which is a key step in the evolution of OLED solid-state lighting. We report practical performance for current high brightness OLED panels and next generation panels, and also discuss some of the key development areas necessary to achieve 100 lm/W efficacy.

4. Acknowledgments

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5. References

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