White Phosphorescent OLEDs: Maximizing the power efficacy lifetime product.

Brian W. D'Andrade, James Esler, Chun Lin, Vadim Adamovich, Sean Xia, Michael S. Weaver, Raymond Kwong and Julie J. Brown
Universal Display Corporation, 375 Phillips Blvd., Ewing, NJ 08618
TEL: 609-671-0980, e-mail: jjbrown@universaldisplay.com

Abstract

High efficacy white OLEDs with low voltage, high quantum efficiency and outcoupling fixtures achieve total power efficacies of 89 lm/W to 102 lm/W, operating voltages between 2.8 V and 3.5 V at correlated color temperatures of 2,800 - 3,900 K and color rendering ~70, at 1,000 nits.

1. Introduction

Advances in white organic light emitting device (WOLED™) technology for general solid-state lighting applications and flat-panel displays have been steady over the last several years. Lighting consumes ~765 TWh of electricity each year in the United States, or nearly 30% of all electricity produced for buildings, which corresponds to 18% of total building energy consumption. In terms of total primary energy consumption, lighting accounts for 8.3% of all the energy used in the United States, or about 22% of all the electricity produced. The power efficiency of WOLEDs has steadily increased over the last twelve years [1] (see Fig. 1), and it seems that the U.S. Department of Energy's (DOE) target energy efficacy of 150 lm/W by 2015 may be attainable by using WOLED technology.

Given these figures, it is clear that increasing the efficiency of lighting by a small amount has the potential to generate tremendous savings in both cost and energy. Incandescent lamps were developed over 100 years ago, and still account for 42% of the electrical energy consumed to produce light [2]. The total power efficacy (PE) of a typical incandescent light bulb is 12-17 lm/W, whereas organic light emitting device (OLED) laboratory demonstrations already have achieved PE = 60-72 lm/W [3], suggesting that there are considerable advantages to be gained by using WOLEDs in this application. However, questions remain of whether WOLED brightness, cost and reliability can all meet the targets of the lighting industry.

WOLED performance advances coupled with the difficulties associated with high resolution shadow masks have made WOLED technology an attractive approach for displays. Among methods for achieving practical WOLEDs, phosphorescence is most effective due to its demonstrated potential for achieving 100% internal quantum efficiency. Phosphorescence has been successfully used to generate the primary colors necessary for display applications, and efficient generation of the broad spectral emission required of a white light source has been reported to exceed that of incandescent bulbs [4]. Here, we report on white all phosphorescent OLEDs, with outcoupling enhancement, that achieved 89 lm/W and 102 lm/W.

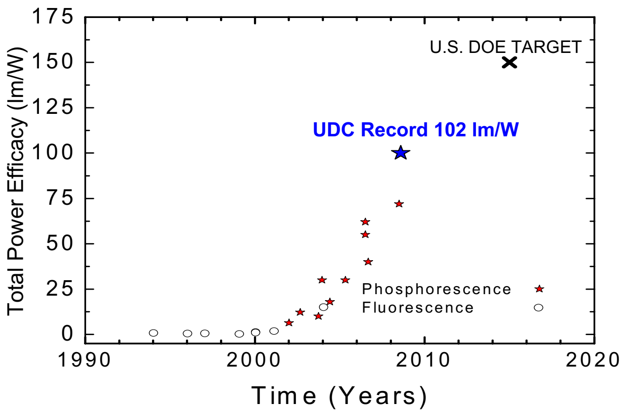

Fig. 1. WOLED power efficacy versus time is plotted. The U.S. DOE luminaire system efficacy goal of 150 lm/W by 2015 is plotted for reference.

2. Experimental

Organic layers were deposited on a transparent conductive oxide. The WOLEDs contained a hole injection layer (HIL) and hole transport (HTL). The emissive layer (EML) consisted of a yellow, red and light blue phosphorescent emitter system. The electron transport layer consisted of a high conductivity undoped material. The main difference in the devices was the different blue hosts, which either enabled very low voltage operation or very high power efficacy. The cathode consisted of 100 nm of Al deposited on 1 nm of LiF, and the 2 mm^2 device active areas were defined by polyimide grid.

All layers were deposited under high-vacuum conditions ($1x10^{-7}$ Torr). The WOLED was transferred directly from vacuum into an inert environment glove-box, where it was encapsulated using a UV-curable epoxy, and a glass lid with a moisture getter.

The PHOLEDs spectral power densities were measured with a SpectraScan PR705. The current and voltage measurements were obtained using a Keithley 236 source measure unit, and the total power efficacy was determined by placing devices, with outcoupling enhancement fixtures [5], in the center of a 20" integrating sphere incorporating a photopic detector.

3. Results and discussion

The WOLED electroluminescence (EL) spectra and an incandescent lamp emission are shown in Fig. 2. Red emission beyond 650 nm is very significant for incandescent emission due to the nature of the source, so WOLEDs with deeper red emission may be necessary for high color rendering above 90. WOLED-1 and WOLED-2 have CIE (0.41, 0.46) and (0.48, 0.46), respectively. The correlated color temperature of WOLED-1 is 3,900 K and WOLED-2 is 2,800 K. It seems that fine tuning of WOLED emitter concentrations, layer thicknesses and charge balance will eventually produce WOLEDs with color rendering indexes (CRI) >75 based on the spectra in Fig. 2. The WOLEDs power efficacies are shown in Fig. 3. Efficacies for WOLED-1 varied between 110 lm/W and 83 lm/W, and WOLED-2 had efficacies between 97 lm/W and 73 lm/W over a range of 100 nits to 5,000 nits. One key difference in the efficacy of these devices is the difference in spectral power density, which effectively differentiates the theoretical maximum efficacy of the WOLEDs and affects the errors associated with using a photopic detector on the integrating sphere.

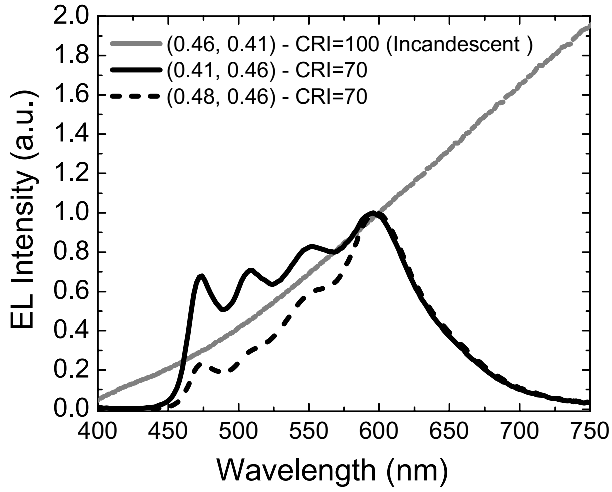

Fig. 2. WOLED-1 (0.41, 0.46) and WOLED-2 (0.48, 0.46) EL spectra are contrasted with emission from an incandescent lamp. The WOLEDs EL have average photon energy between 2.1 eV and 2.2 eV.

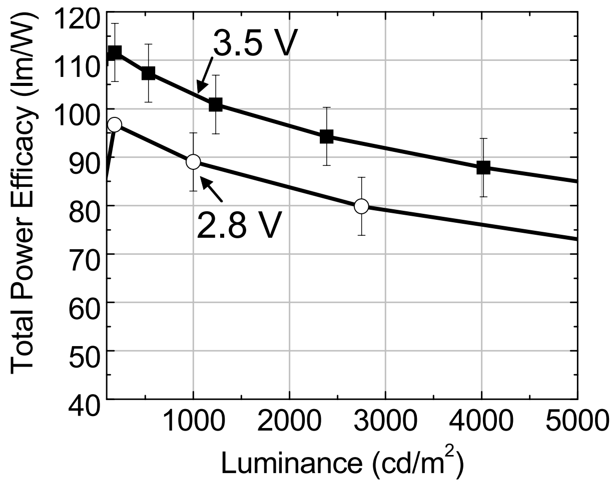

Fig. 3. Due in part to the different spectral power densities, the efficacy of WOLED-1 (squares) is 102 lm/W and WOLED-2 (circles) is 89 lm/W at an effective Lambertian luminance of 1,000 nits. The WOLED efficacies were measured with outcoupling enhancement fixtures.

Future efforts to improve the CRI of devices will affect the theoretical maximum efficacy of WOLEDs, so lighting panel operating voltages and external quantum efficiency will continue to be improved in the near future.

The key to the high efficacy is phosphorescence; additionally, the device architecture enables high efficiency due to the material and layer structure designs. Low operating voltage is also of high importance. These devices are able to operate at low voltage without the use of conductivity doped transport layers because of the nature of the interfaces between the hosts and the transport layers.

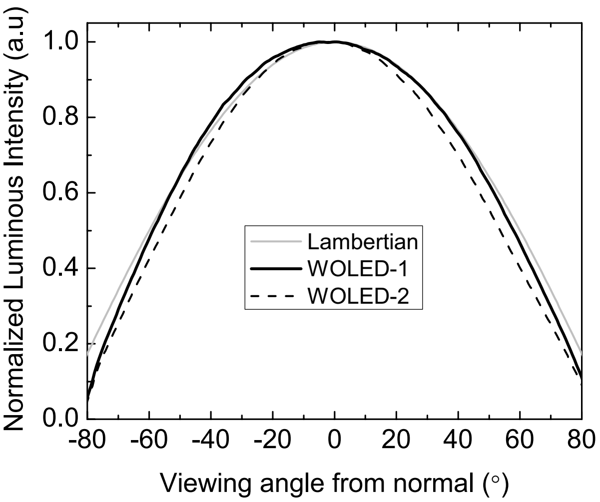

Fig.4. The normalized candela (luminous intensity) versus viewing angle is plotted for both WOLEDs (without outcoupling fixtures) and a Lambertian emitter. WOLED-1 emission intensity is higher than WOLED-2 emission at all angles.

Figure 4 shows the normalized luminance intensity (normalized candela), without outcoupling enhancement, for WOLED-1, WOLED-2 and a Lambertian emitter. Both WOLEDs have lower intensity, at off-normal angles, than a Lambertian emitter; however, WOLED-1 maintains a Lambertian emission pattern up to 40º whereas WOLED-1 follows a Lambertian emission pattern to 10º. The difference in the emission pattern of these WOLEDs also contributes to the difference in the total power efficacy shown in Fig. 3.

Both WOLEDs emission colors vary slightly with viewing angle. The CIE x decreases by <0.05 and the CIE y increases by <0.02 as the viewing angle increases from 0 º to 80 º from the substrate normal. This CIE shift represents an average shift Δu'v'=0.017.

The time to 50% initial luminance at 1,000 nits for WOLED-1 and WOLED-2 is 8,000 hrs and 5,000 hrs, respectively. This lifetime was extrapolated from accelerated driving conditions without any outcoupling enhancement fixtures, and the difference in color between an unaged and aged device is Δu'v'<0.015.

In conclusion, high efficacy white OLEDs with low voltage, high quantum efficiency and outcoupling fixtures achieve total power efficacies of 89 lm/W to 102 lm/W, operating voltages between 2.8 V and 3.5 V at correlated color temperatures of 2,800 K - 3,900 K and color rendering ~70, at 1,000 nits.

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6. References

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