An imaging-based photometric and colorimetric measurement method for characterizing OLED panels for lighting applications

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ABSTRACT

The organic light-emitting diode (OLED) has demonstrated its novelty in displays and certain lighting applications. Similar to white light-emitting diode (LED) technology, it also holds the promise of saving energy. Even though the luminous efficacy values of OLED products have been steadily growing, their longevity is still not well understood. Furthermore, currently there is no industry standard for photometric and colorimetric testing, short and long term, of OLEDs. Each OLED manufacturer tests its OLED panels under different electrical and thermal conditions using different measurement methods.

In this study, an imaging-based photometric and colorimetric measurement method for OLED panels was investigated. Unlike an LED that can be considered as a point source, the OLED is a large form area source. Therefore, for an area source to satisfy lighting application needs, it is important that it maintains uniform light level and color properties across the emitting surface of the panel over a long period. This study intended to develop a measurement procedure that can be used to test long-term photometric and colorimetric properties of OLED panels. The objective was to better understand how test parameters such as drive current or luminance and temperature affect the degradation rate. In addition, this study investigated whether data interpolation could allow for determination of degradation and lifetime, L_{70}, at application conditions based on the degradation rates measured at different operating conditions.

Keywords: organic light-emitting diode, OLED, lumen maintenance, imaging based, photometric measurement, colorimetric measurement

1. INTRODUCTION

The organic light-emitting diode (OLED) is a solid-state lighting technology that has potential to save energy and provides novel solutions in certain lighting applications. For OLED technology to gain widespread adoption in lighting applications, a standardized vocabulary, definitions, and metrics are needed. Currently, there is no industry standard for measuring and reporting OLED lumen depreciation. Published data from manufacturers of OLED panels are not easy to compare because they are not tested under similar electrical and thermal conditions. The objective of this study was to better understand the factors that influence lumen depreciation with the intention of developing a measurement procedure for lumen depreciation testing of OLED panels.

1.1 Impact of electrical stress on OLED lumen depreciation

Past studies have discussed the degradation mechanisms for OLEDs, including dark spot formation, photo-oxidation, recrystallization, metal atom migration, molecule-specific degradation processes as well as electrical breakdown.[1,2] Similar to light-emitting diode (LED) technology, the lumen depreciation of an OLED is affected by electrical and thermal properties. Tyan et al. have shown that when current flows through the OLED device, there is a gradual decrease in light output caused by chemical degradation of the organic materials.[3] Lumen depreciation seems to depend on the drive current, given by

$$I^n L_x = \text{Constant} \tag{1}$$

where I is the operating current, L_x is the lifetime (in hours, defined by the time it takes for the light level to reach a certain threshold value), and n is the exponent that depends on the device design.[3,4] The reported values of the exponent, n, is either 1 or 1.5.[3,4] Other studies have shown a similar relationship between initial luminance and lifetime[5,6], which is due to the nearly linear relationship between luminance and drive current.

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1.2 Impact of thermal stress on OLED lumen depreciation

Levermore et al. have shown that lifetime decreases with increasing temperature following an exponential decay function, and the decay rate follows the Arrhenius equation, which is temperature dependent.[7] According to Levermore et al., the rule of thumb is for every 10°C decrease in temperature the lifetime increases by 1.65 times.[7]

Cester et al. investigated the impact of both the electrical and thermal stress on OLED lumen depreciation and found that thermal stress alone did not affect optical or electrical performance of an OLED device. Any degradation is strictly related to the current flow.[8] Furthermore, they found the optical power degraded faster at higher operating temperatures while the device was powered on and the voltage increased at higher operating temperatures.[8] Cester et al. discovered a good correlation between the operating voltage increase and the optical power reduction, independent of the stress temperature.[8]

Presently, there is no standardized method for temperature measurement of an OLED device, and manufacturers use different temperature measurement locations. Levermore et al. mentioned measuring the OLED panel surface temperature at the center of the emissive region using a k-type thermocouple.[7] Kawabata et al. mentioned using an infrared thermometer and an imaging infrared camera to measure the OLED panel surface temperature.[9,10] Pang et al. mentioned the voltage drop method ("K-factor") to indirectly measure the OLED junction temperature.[6]

The objective of this study was to conduct a luminance degradation study using an imaging photometer system to understand how test parameters such as drive current or luminance and temperature affect the degradation rate. In addition, this study investigated whether data interpolation could allow for determination of degradation and lifetime, L_{70},[11,12] at application conditions based on the degradation rates measured at different operating conditions.

2. EXPERIMENT

In this study, two types of commercial white OLED products (panel A and panel B) were selected. The emitting surface areas for panel A and panel B are 104 mm by 104 mm and 90 mm by 90 mm, respectively. Each product was tested at two different drive current values, rated current and maximum allowed current (or a higher current if maximum current was not specified by the manufacturers). The ambient temperatures near the panels were controlled at 38°C for all four tested OLED panels. Temperatures were monitored at the OLED front panel (emitting side) using a thermocouple attached at the hottest point, which was identified by using an imaging infrared camera prior to the long-term test.

Figure 1 illustrates the experiment setup. Each OLED panel was placed vertically to mimic a display application in an enclosed wooden box, in which the ambient temperature was monitored and controlled. Photocells were mounted in each test box viewing the OLED panel. The spectral response of the photocells used in the experiment matched the luminous efficiency function of the human eye at photopic conditions, V(λ), and the angular response of the photocells was cosine. Therefore, the photocell functioned similar to an illuminance meter monitoring the relative light output of each OLED panel throughout the long-term test. Periodically, the cover of each temperature-controlled wooden box was replaced by a transparent acrylic cover, and the imaging photometer system was used to measure the luminance and the chromaticity of each OLED panel.

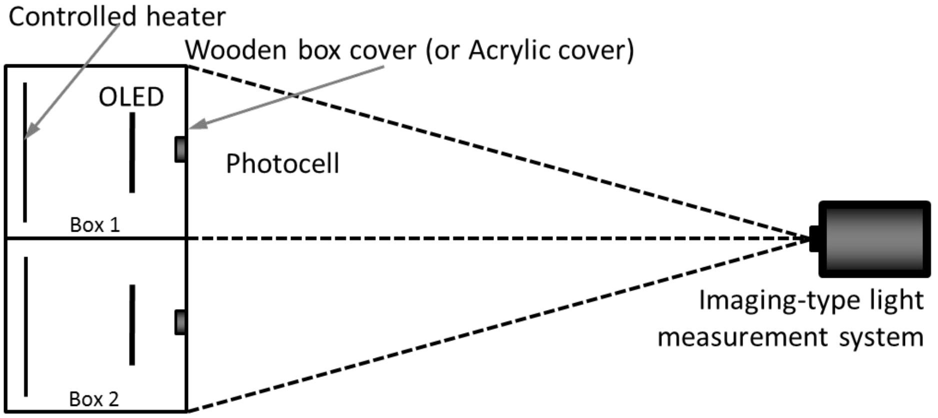
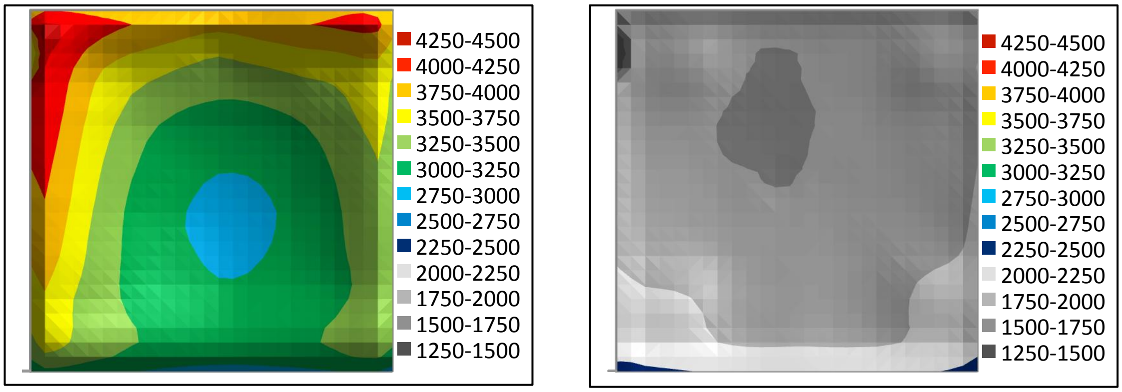


Figure 1. Schematic of the experiment set-up for long-term testing of the OLED panels.

3. EXPERIMENT RESULTS AND ANALYSES

Figure 2 (a) and (b) illustrate the luminance distributions of OLED panel A operated at rated current of 500 mA, at 0 and at 13730 hours, respectively. Figure 3 illustrates the relative luminance ratio, at 13730 hours compared with 0 hour for the same OLED panel operated at rated current of 500 mA. In this case, the OLED panel luminance degradation was highest at the top and lowest at the middle part of the panel. This is most likely due to two reasons: the initial luminance was higher at the top of the panel, which resulted in higher degradation at the top of the panel than at the bottom of the panel; and the ambient temperature surrounding the OLED panel was found to be approximately 5°C higher at the top of the panel than at the bottom of the panel due to heat convection inside the temperature-controlled box, which led to higher degradation at the top of the panel than at the bottom.



(a) (b)

Figure 2. Luminance (cd/m^2) of OLED panel A operated at rated current (500 mA) at: (a) 0 hour; (b) 13730 hours.

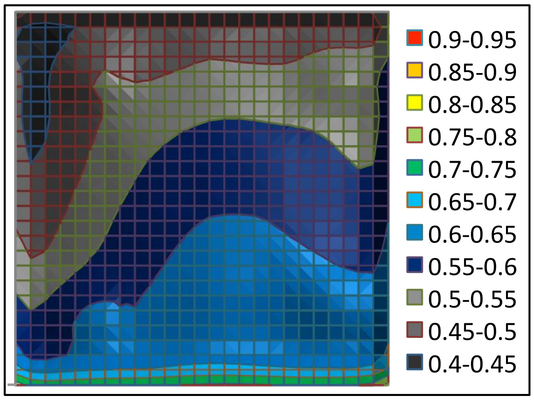
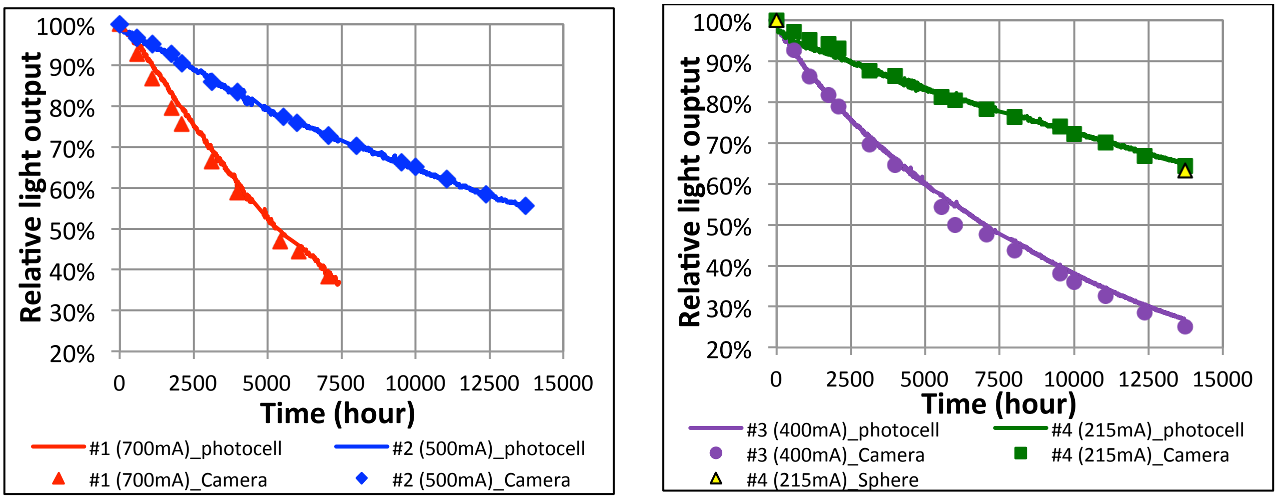


Figure 3. Ratio of luminance at 13730 hours to the initial luminance for OLED panel A operated at rated current (500 mA).

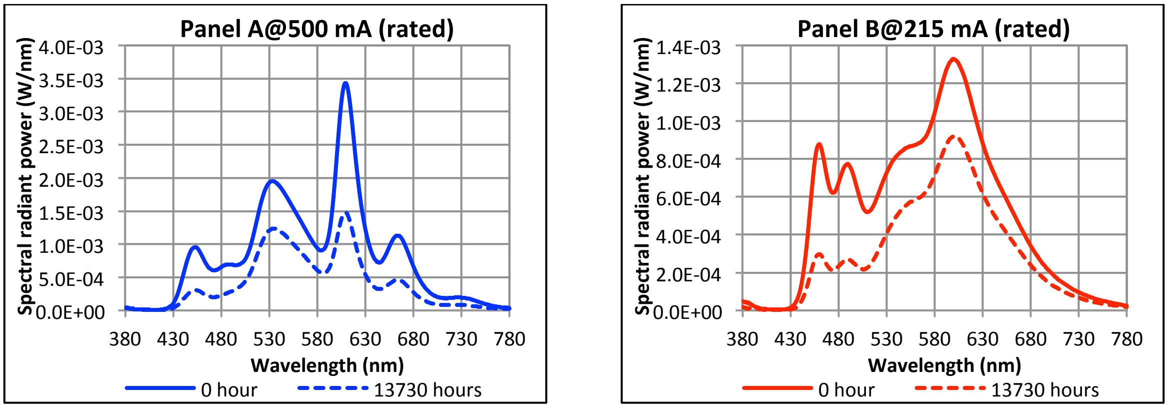
The luminance depreciations for panel A and panel B operated at rated and higher current are shown in Figure 4 (a) and (b). Under each testing condition: photocells were used to continuously monitor the relative light output throughout the test; an imaging camera was used periodically to test the luminance of each OLED panel and the averaged luminance is plotted as a function of testing time. For OLED panel B operated at rated current of 215 mA, integrating sphere measurements for total luminous flux at 0 hour and 13730 hours (end-of-test) were carried out. All three photometric measurement methods showed similar results for the relative lumen depreciation values. For both panel A and panel B, the results show that the OLED panels degraded faster at higher current when the ambient temperature was held constant. The interpolated L_{70} values for panel A and panel B at rated current and ambient temperature of 38°C are 8149 hours and 10885 hours.



(a) (b)

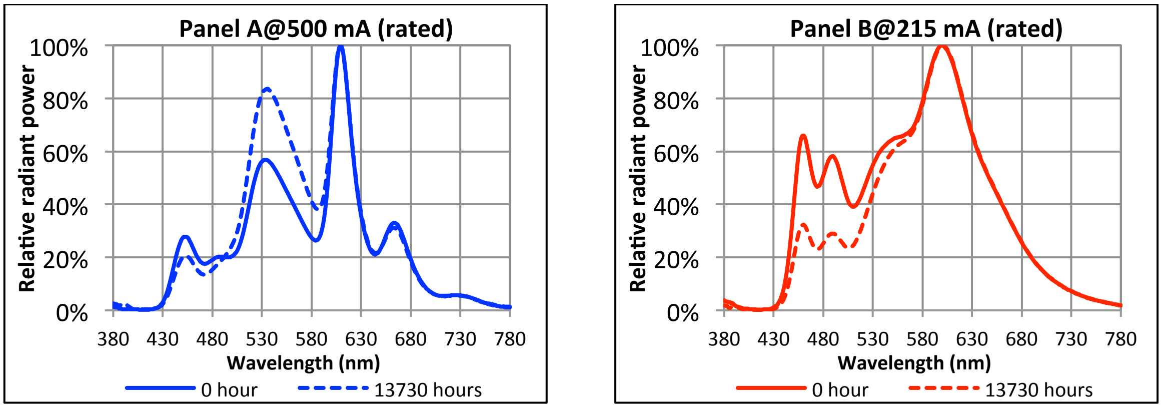
Figure 4. Lumen depreciations of: (a) Panel A at higher current of 700 mA (condition #1) and rated current of 500 mA (condition #2); (b) Panel B at higher current of 400 mA (condition #3) and rated current of 215 mA (condition #4).

The initial and end-of-test (at 13730 hours) spectral power distributions of panel A and panel B operated at rated current are shown in Figure 5(a) and (b). Their spectral power distributions are normalized in Figure 6(a) and (b). Results show that there was an increase in the green spectral component in panel A, which led to a chromaticity shift towards “green” for panel A, while there was a decrease in the blue spectral component in panel B, which led to a “red” shift. Figure 7 shows the chromaticity coordinates of panel A and panel B operated at rated current at 0 hour and 13730 hours. The corresponding color shift for panel A and panel B is 27 and 25 MacAdam steps, respectively.



(a) (b)

Figure 5. Spectral power distributions of: (a) panel A operated at rated current (500 mA) at 0 hour and 13730 hours; (b) panel B operated at rated current (215 mA) at 0 hour and 13730 hours.



(a) (b)

Figure 6. Normalized spectral power distributions of: (a) panel A operated at rated current (500 mA) at 0 hour and 13730 hours; (b) panel B operated at rated current (215 mA) at 0 hour and 13730 hours.

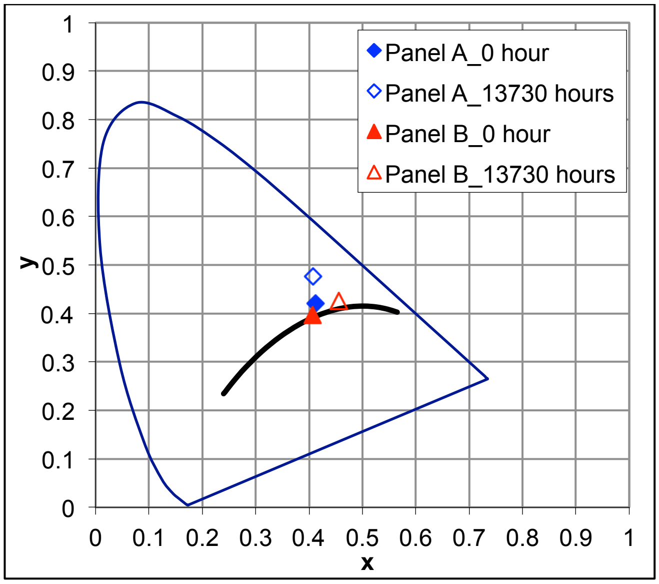


Figure 7. CIE 1931 chromaticity diagram of panel A and panel B operated at rated current at 0 hour and 13730 hours.

The relationship between lifetime and drive current was analyzed following a mathematical model mentioned in the previous studies.[3,4] Figure 8 shows lifetime— L_{70}, L_{80}, and L_{90}—plotted as a function of drive current for both panel A and panel B. L_{70}, L_{80}, and L_{90} values were interpolated from the experimental results. Power function [equation (1)] was applied to fit the experiment results. It was found that for panel A, the exponent is 3.3, 3.3, and 3.0 for L_{70}, L_{80}, and L_{90}, respectively; for panel B, the exponent is 2.0, 2.0, and 2.3 for L_{70}, L_{80}, and L_{90}, respectively. These exponent values are much higher than the 1.0 to 1.5 values mentioned in the past studies.[3,4]

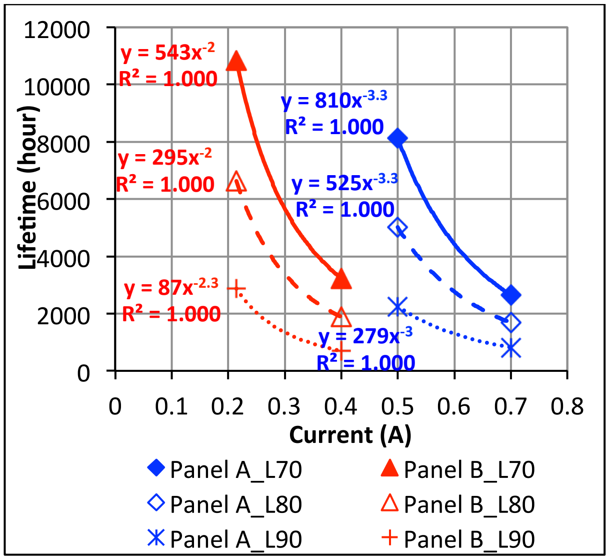


Figure 8. Lifetime (L_{70}, L_{80}, and L_{90}) as a function of drive current for panel A and panel B.

Assuming the relationship between luminance and drive current is linear; the experiment results can be fitted as shown in Figure 9 using a linear function. Lifetime L_{70} as a function of drive current for panel A and panel B in Figure 8 can be converted to L_{70} as a function of luminance, which is plotted in Figure 10. If manufacturers test the lumen maintenance of their OLED panels at two or more luminance levels and interpolate or extrapolate the L_{70} values, a similar chart to Figure 10 can be generated. Therefore, the L_{70} value at any other luminance level within the tested luminance range can be interpolated or extrapolated (if no other degradation mechanism occurs outside the tested luminance range).

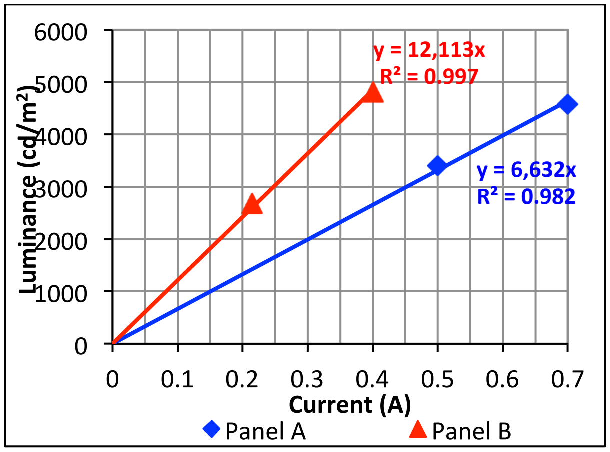


Figure 9. Linear fit of luminance versus drive current (A).

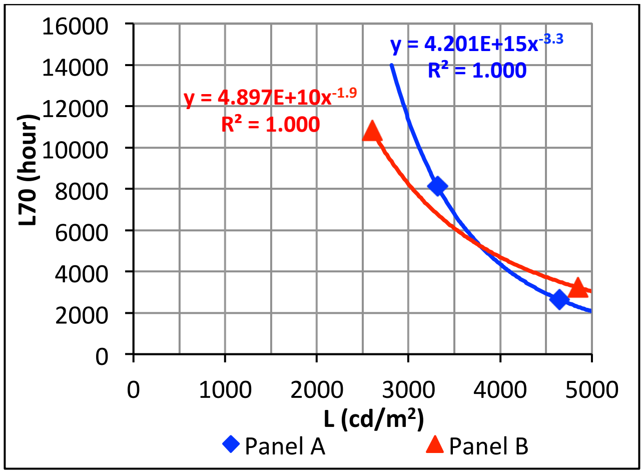


Figure 10. Lifetime (L_{70}) as a function of luminance for panel A and panel B.

4. CONCLUSIONS

Based on this preliminary study results, testing the OLED panels at a given ambient temperature at different current levels and plotting the average L_{70} as a function of average panel luminance allows for the determination of the average L_{70} at any application luminance. For the present OLED devices, 6000 hours of data collection (consistent with the LED lumen maintenance test method[12]) is sufficient to accurately estimate L_{70} values.

Since an OLED is a large area source, it may not be sufficient to know only the average luminance degradation. A useful lifetime definition needs to include luminance uniformity and color uniformity. For the uniformity analysis, area bin sizes corresponding to certain spatial frequencies must be defined based on visual performance. Also, to develop a standard measurement procedure for lumen maintenance testing of OLED panels, test luminance values based on typical application range, temperature measurement method and temperature test point(s), and OLED panel operation orientation must be specified.

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