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P-54: Scalability of OLED Fluorescence in Consideration of Sunlight-Readability Reflection Measurements

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Abstract
The fluorescence characteristics of an OLED material are demonstrated to be linear with sunlight-like illuminance levels up to several suns. It is therefore possible to make laboratory reflection measurements with much lower illuminance levels and scale them to sunlight levels to qualify such displays for sunlight readability.

1. Introduction
Display sunlight readability measurements have historically been performed by using full-sun illumination levels. The presumption is that this direct method would take into account any possible nonlinear artifacts of the optical system, and result in a more accurate measurement. However, requiring sunlight levels for the measurement is a difficult requirement to meet considering the expense and difficulty of providing the proper sunlight-level illumination and correct spectrum. It would be much better to permit lower-light-level illumination under laboratory conditions, and then scale the results to sunlight levels. But it must first be confirmed that the display has a linear optical response up to these high illumination levels

As with other emitting displays, OLED (organic light-emitting diode) displays contain materials that can fluoresce when exposed to sunlight. There is a concern that the fluorescence emitted by such displays may exhibit saturation at full sunlight levels. If florescence saturation were to occur, it would prevent the use of scalable reflection measurements and require full sunlight illuminance at the correct spectrum. This paper shows that the fluorescence of a common large-molecule OLED is indeed linear and scalable, even up to illuminance levels of several suns. It is further shown how a possible sunlight-readability test might be performed based upon scaling.

2. Apparatus
Figure 1 shows a diagram of the experimental setup. A scientific-grade 16–bit CCD (charge-coupled device) camera with a photopic filter is used to view the OLED sample through a 60 mm lens stopped down to f/22 with a 1 s exposure. The OLED sample is held in place with a sponge-rubber block gently pressing its front surface against four corner brackets so that the sample can be removed and replaced in the same plane. Figure 2 shows the OLED device powered on, where the left and bottom profiles indicate the surface luminance uniformity cross-sections acquired by the camera. The OLED sample is prepared only for laboratory experimentation, where uniformity is not an important consideration.

A white reflectance standard made of sintered powdered PTFE (polytetrafluoroethylene) of the same size as the OLED sample can be interchanged with the OLED sample to make illuminance

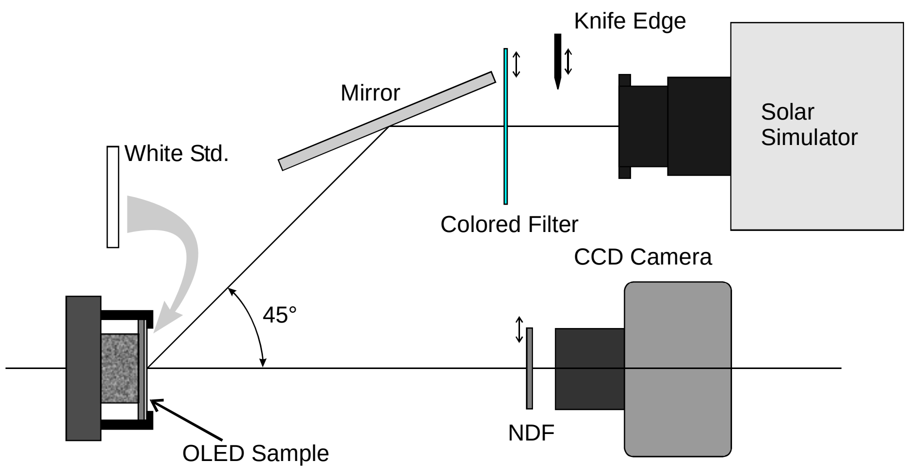

Fig. 1. *Apparatus configuration. A white standard can be interchanged with the OLED sample for illuminance measurements, a colored filter can be inserted to change the spectral distribution, a knife edge can be introduced to dramatically change the uniformity of the light distribution on the sample surface, and a neutral-density filter (NDF) can be inserted to avoid overexposure.*

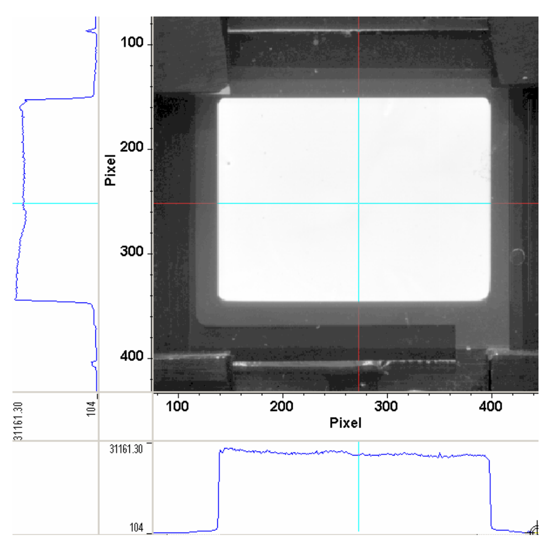

Fig. 2. *OLED sample turned on (powered).*

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measurements. At an incident illumination angle of approximately 45°, the luminance factor is approximately one (β = 1, +0 %, –3 %), so the illuminance E can be determined from the luminance L via $L = \beta E/\pi$. The CCD camera can also be replaced with a spectroradiometer for spectrally resolved radiance measurements. Given the phenomenological nature of this paper, and that the conclusions are based primarily upon relative luminance measurements of the sample and the white standard, the luminance and radiance measurements have uncertainties of ±5 % [expanded uncertainty with a coverage factor of two]. Under the conditions used in these experiments, if fluorescence saturation were present, we would be anticipating errors by factors of two or more, not a few percent.

In the measurement geometry (Fig. 1), a neutral-density filter (NDF) can be inserted just before the CCD camera to limit the light entering the camera for the particularly bright configurations. Colored filters can be inserted into the light path to change the spectral distribution of the source, and a knife-edge can be used to dramatically change the uniformity of the illuminance distribution on the samples. The CCD camera array has a uniformity of approximately ±1 % and the subtense of the sample from the camera is only a few degrees, thus no flat-field correction is needed for these comparative or illustrative measurements, and only a background subtraction is employed. The active area of the OLED sample is 30 mm wide by 20 mm high, and fabricated using a commercially available yellow OLED material (made by Covion [1]). This material is integrated into a standard unpixellated backlight structure. The sample is placed approximately 500 mm from the front of the lens of the CCD camera. The subtense of the sample is less than 2°. The OLED sample is operated at a luminance of approximately 128 cd/m^2 for this investigation. The OLED backlight does not have any contrast enhancement filters or coatings because the basic reflection properties of the bare display are of interest in these tests.

3. Results

Figure 3 shows the nonuniform illumination of the sample area with a peak of approximately five sun equivalents. Assuming that the solar illuminance is

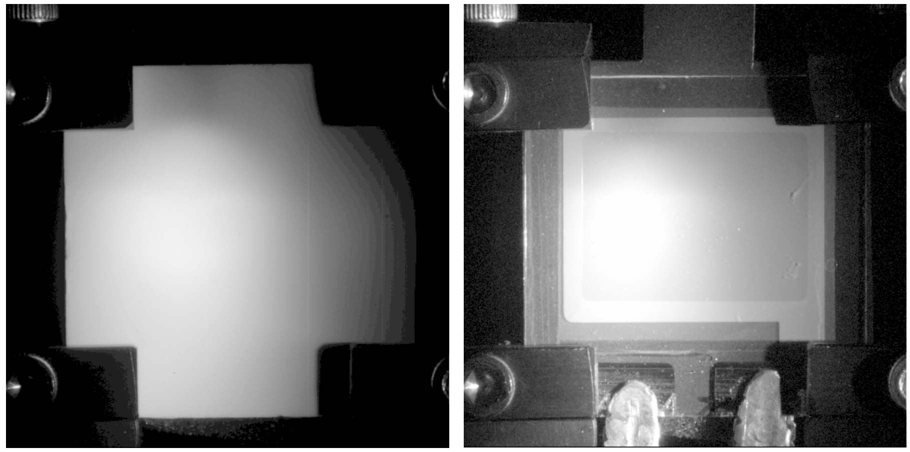

Fig. 3. *Nonuniform illumination on the white standard (left) and OLED sample (right). Non-Lambertian nature of the OLED sample is evident.*

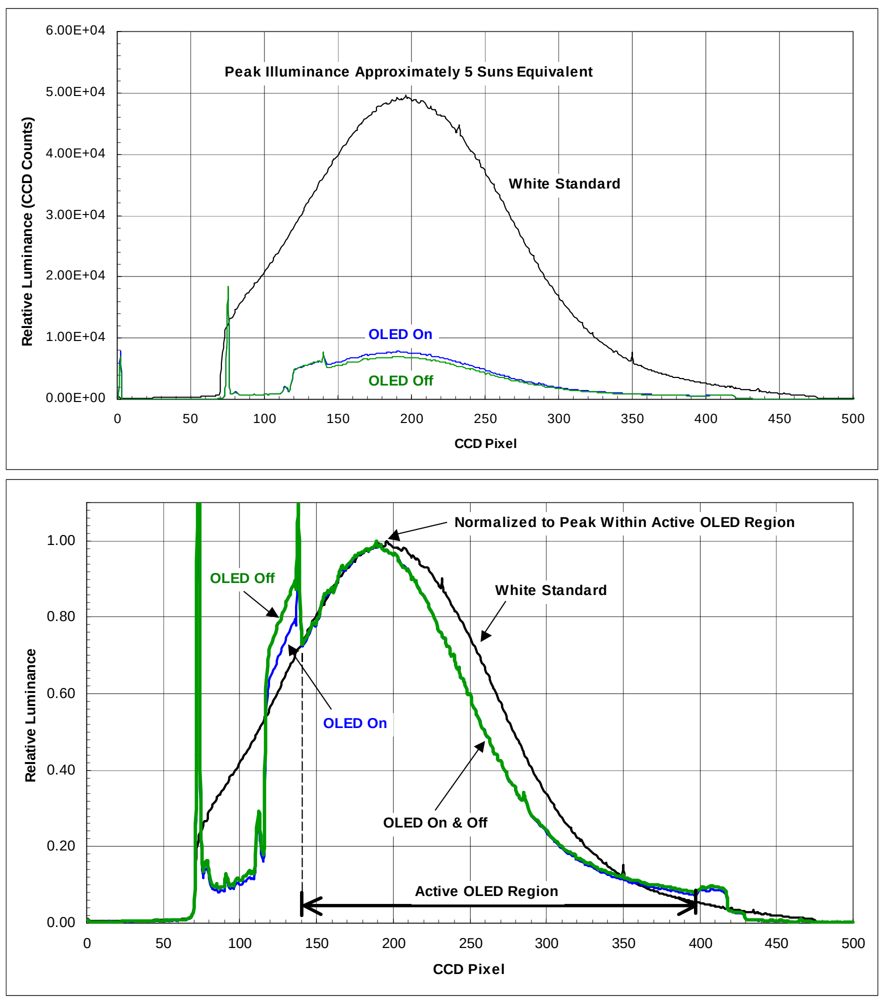

Fig. 4. *Luminance profiles of white standard, OLED on, and OLED off. Normalized profiles are shown in the bottom graph where the OLED profiles in the active region overlap. The details to the left (and right) of the active OLED region are from reflections off the surfaces surrounding the OLED material.*

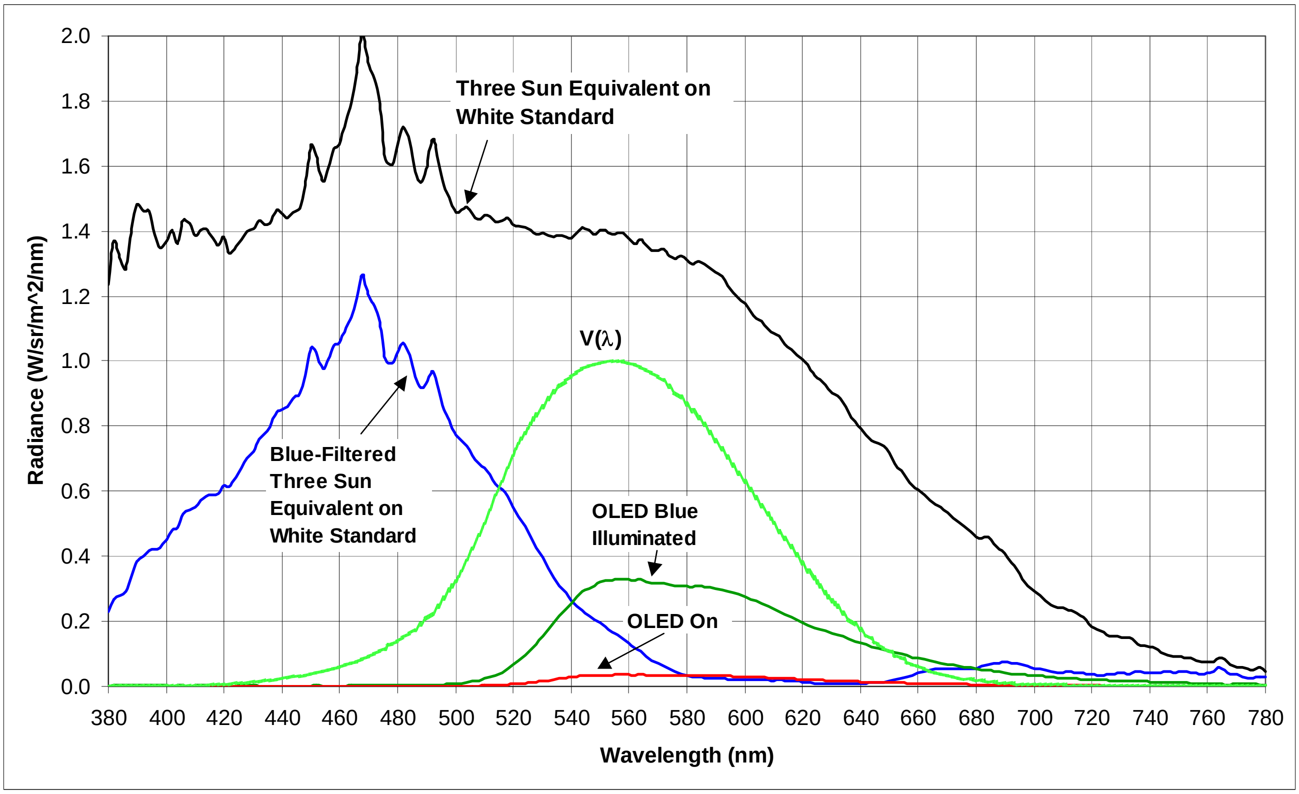

Fig. 5. *Spectra of illuminants (unfiltered and blue with infrared cutoff filtration) and the OLED's response. The spectral luminous efficiency for the human eye V(λ) is added for reference.*

10^5 lx, the luminance of a perfectly reflecting diffuser would be 31 821 cd/m^2. Five solar equivalents would exhibit a luminance of approximately 1.6×10^5 cd/m^2 on the white standard. This luminance level is actually measured at the brightest spot on the white standard (left image in Fig. 3).

Figure 4 shows the average horizontal luminance profiles for a narrow horizontal box intersecting the brightest part of the CCD images in Fig. 3. If fluorescence saturation were present then we would see a flat-top behavior in the OLED normalized curves in Fig. 4. As the illumination approached the peak region there would be less reflected luminance. However, just the opposite is actually observed. Of course, it would have been more convincing if all three normalized curves overlapped. The reason that they do not overlap is probably due to the nature of the reflection for the OLED sample being different from that of the quasi-Lambertian white standard. This assertion is supported by comparing the two images in Fig. 3. If the reflection properties were the same then similar images should have been produced. As it is, the OLED image shows a stronger peak at the hot spot, as indicated in the normalized curves of Fig. 4. These results provide a strong indication that there is no fluorescence saturation, but more quantitative measurements are obtained to support this finding.

Replacing the CCD camera with a spectroradiometer with a narrow measurement field angle of 0.125° permits the spectral characterization of the reflection properties and fluorescence. Figure 5 shows the spectrally resolved radiance for an illumination of approximately three solar equivalents. A blue filter is combined with an infrared cutoff filter to provide a blue illumination that is roughly equivalent to two suns in the blue region. Figure 5 contains the spectrum of the solar-simulated light incident upon the white standard, the spectrum after the blue filter combination is inserted, the spectrum of the OLED sample turned on, and the spectrum of the OLED sample

Table 1. *Radiance ratio of reflected vs. incident blue illumination. **

Blue illumination on White Std.		OLED	Ratio
Luminance L_{vB} (cd/m^2)	Radiance L_{eB} (W/sr/m^2)	Reflected Radiance L_{eO} (W/sr/m^2)	$\boldsymbol{L_{eO}/L_{eB}}$
46.5	0.900	0.107	**11.9 %**
88.4	1.68	0.203	**12.1 %**
232	4.55	0.532	**11.7 %**
695	13.6	1.59	**11.7 %**
1730	33.5	3.92	**11.7 %**
6960	127	15.7	**12.3 %**

*We provide the luminance levels for comparison purposes. Expanded uncertainties with a coverage factor of two for luminance and radiance are approximately 4 %. The uncertainties in the radiance ratios are much smaller (because of covariance terms); the expanded uncertainties with a coverage factor of two for the radiance ratios are estimated to be 0.5 %.

hit with the blue illumination with the backlight on. Clearly, the blue light is responsible for the yellow fluorescence. These curves are all for the brightest illumination employed in this sequence of measurements.

To demonstrate the absence of fluorescence saturation, the radiance L_{eB} of the incident blue light is compared against the radiance L_{eO} of the light reflected from the OLED sample with increasing blue illumination. The ratio L_{eO}/L_{eB} is an indication of how well the fluorescence scales with the illumination level. If that ratio remains constant, then there is no fluorescence saturation. Table 1 summarizes the results, demonstrating that fluorescence saturation is not a problem for this OLED material when illumination levels of two suns or less are used.

4. Conclusion

The results obtained demonstrate that the fluorescence of the OLED material does not saturate and is linear for several sun illuminance levels. Therefore, reflection measurements can be performed at much lower levels in the laboratory and then scaled to daylight conditions. If the display or material does not exhibit color or fluorescence, then the reflection properties will be spectrum independent for most types of reflection measurements. If the material is colored or exhibits a strong fluorescence, then careful attention may have to be paid to the spectral content of the illumination employed.

As an example of a sunlight-readability test utilizing scalable reflection measurements, consider the following method: The desired illumination conditions representing full daylight might be a uniform (diffuse) ambient illuminance of $E_a = 6000$ lx and a directed sunlight illuminance of $E_s = 100\,000$ lx from an angle of 45° above the normal. Suppose the display does not exhibit fluorescence or any color (i.e., if it is dark gray or black in appearance) so that the spectral distributions of the light sources employed are not important factors. Two separate laboratory measurements are made using available sources (see Fig. 6). The results are appropriately scaled to daylight levels as follows: (1) Perform a diffuse illumination measurement ($\theta_d = 8°$ to 10°) of the display obtaining the diffuse reflectances of white (display on) and black, ρ_W and ρ_K ($\rho = \pi L/E$). [2] Then (2) perform an isolated source measurement at 45° above the normal ($\phi_s = 90°$, $\theta_s = 45°$) employing a source with a subtense of 0.5° (the angular subtense of the sun and moon) and obtain the luminance factors for white and black, β_W and β_K ($\beta = \pi L/E$). The resulting scaled contrast for sunlight readability of the display for the specified daylight conditions will be

$$C_s = \frac{\pi L_W + \rho_W E_a + \beta_W E_s}{\pi L_K + \rho_K E_a + \beta_K E_s}\,, \qquad (1)$$

where L_W and L_K are the white and black luminances of the display as measured in a darkroom (they are obviously zero for reflective displays). For displays that do exhibit fluorescence, the correct illumination spectrum (not intensity) for the ambient source and correct illumination spectrum for the directed source (sun simulator) must be used (they will not necessarily have the same spectrum). The effects of fluorescence would then be contained within the diffuse reflectance and the luminance factors.

This paper has demonstrated that the yellow OLED material used in this investigation has fluorescence properties that scale linearly up to multiple suns. However, this linearity needs to be verified for other OLED materials of interest before applying a scaling reflection measurement method. Once confirmed, the ability to make reflection measurements on displays in the laboratory using readily available illuminants and lower light levels not only saves time and money, it is also much safer for the people making the measurements. They no longer have to deal with illuminants at solar levels that can harm the eyes. In addition, demonstrating the applicability of the reflection method offers the opportunity to model displays at arbitrary illumination levels and spectra.

5. Acknowledgements

The authors thank Ian Parker and Chi Zhang of DuPont Displays for providing the test samples for this investigation.

6. References

[1] Any commercial item referred to in this paper is for the purpose of identification only. Such a reference does not imply a recommendation or endorsement by the National Institute of Standards and Technology, neither does it suggest suitability to task.

[2] E. F. Kelley, "Proposed Diffuse Ambient Contrast Measurement Methods for Flat Panel Displays," NISTIR 6738, 6 pp., April 2001. See also the *Flat Panel Display Measurements Standard* (FPDM), Video Electronics Standards Association, Version 2.0, Section 308 (in particular Section 308-2), p. 139, June 1, 2001.

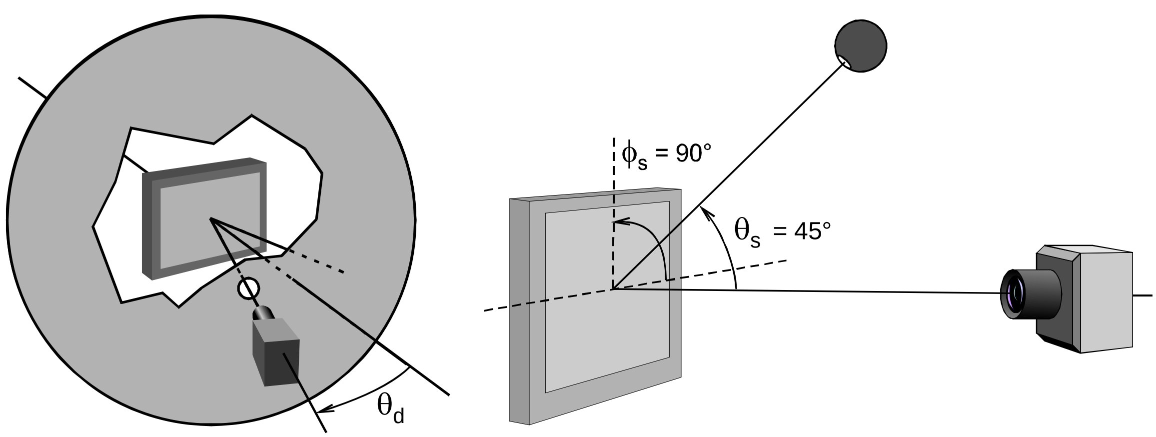

Fig. 6. *Example of sunlight readability testing configurations where two separate measurements are made, combined, and scaled to daylight levels.*