Errors in organic light emitting diode measurements

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Abstract

External quantum efficiencies of organic light emitting diodes have improved substantially over the last decade, but theoretical efficiency limits are often contradicted by empirical results. An examination of sources of errors in the measurement of devices suggests that theory and accurate measurements may better coincide if appropriate corrections are considered. Methodological, instrument, electronic, and optical sources of errors are discussed, and some estimations of the magnitude of individual errors are provided in this paper. Errors in efficiency calculations of about 2% are almost unavoidable but errors of or greater than 10% may exist.

1. Introduction

The external quantum efficiency (EQE) of organic light emitting diodes (OLED) has significantly improved over several years. Early theories estimated a forward viewing EQE approaching 20% [1], and later calculations showed values exceeding 20% with optimized OLED optical cavities [2, 3]. Today, there are commercially available software packages that provide predictive optical data for OLED cavity designs [4]. Theoretical and empirical values, however, sometimes do not match either because theories need refinement or because of measurement error. Often, there is consistency in the measurement methods used for efficiency characterization, but this consistency has errors that may persist. For example, the United States Department of Energy has a solid-state lighting commercial product testing program [5] and found that a 2.9% difference in measured lumen output and a 1.6% variation in efficacy existed between two commercial light testing laboratories that performed the same measurements.

This paper presents several sources of measurement errors that affect calculated values such as EQE and power efficiency, and it discusses how potentially inaccurate empirical results veer away from theoretical values. Some examples available in the literature are provided in the references, but quality, processing, manufacturing and other issues will affect individual devices and all devices do not possess the errors of the same magnitude as discussed in this article.

There are three physical quantities of an OLED that are useful to characterize some properties of a device under test (DUT): current, voltage, and optical power. The most difficult quantity to measure is optical power and either the total optical power or the forward-viewing optical power is desired to calculate efficiency. There are several methods to determine the optical power over a range of current densities or operating voltages.

One method uses a luminance meter or spectroradiometer to measure the normal luminance/radiance at all current densities of interest. A second method uses a calibrated silicon photodetector to measure the optical energy at all current densities [6]. A third method is a hybrid method of the first two methods, where the luminance at a set current density is measured with a luminance or spectroradiometer. The set current density and associated luminance are used to calibrate a silicon photodetector that is then used to measure the relative optical output for a given current [7]. These three methods rely on assumptions about the emission pattern of the OLED to derive additional quantities. For example, the forward emission pattern is frequently assumed to be Lambertian. A fourth method [8] uses an integrating sphere for optical measurements and the Illuminating Engineering Society of North America has developed the LM-79-08 standard to measure light emitting diode power efficacy [9] using an integrating sphere.

Each measurement method will be affected by sources of error and the magnitude of the errors may be different for each method. For convenience, errors may be sorted into three categories, instrument, electronic, and optical, and those three categories of errors will be discussed in the proceeding sections.

2. Instrument and Physical Errors

Instrument errors are mainly due to limitations of specific equipment but unawareness of the limitations may also contribute to errors. It would be impractical to list the errors for each piece of equipment here, but it is important to realize that the errors may be significant. A few pieces of equipment are discussed below.

Each piece of equipment usually has a calibration report and the equipment error margins will be stated on the calibration report. For example, an HP4155 will typically have extremely low current and voltage errors for most OLED characteristics of interest; however, a spectroradiometer or luminance meter may have a ±2% to ±4% optical error against an Illuminant A based (2856 K) NIST traceable luminance standard. A luminance meter may have additional errors if photopic filters are used to determine the luminance because a photopic filter cannot accurately replicate the photopic luminosity curves, so color correction factors are necessary when measuring non-standard sources. For example, a luminance meter has a color correction factor of 1.123 when measuring blue [10].

Other equipment errors may be more nuanced. For example, an integrating sphere is often calibrated with an incandescent lamp whose spectral power distribution may be described by the Blackbody equation. If the DUT in an integrating sphere does not have the same spectral power distribution of the calibration source, one may expect that there will be larger errors in the DUT optical measurement than optical measurement errors associated with a device having emission comparable to the calibrating lamp emission. For high precision, an integrating sphere optical power may be calibrated at multiple wavelengths to reduce errors.

The area of an OLED should ideally be measured whenever an OLED is being characterized because the OLED area is not constant. Features produced by shadow masks, for example, used in a vacuum thermal evaporation system will probably be larger than the dimensions of the feature on the shadow mask. This occurs because there may be a gap between the substrate and the mask, so material may be deposited under the mask [11]. OLED areas defined by polyimide or other materials will also change because the polyimide recedes and expands depending on processing conditions. The error in the area varies depending on a given process and will be minimized by sufficient fabrication quality control, but it may be as much as 10% without appropriate controls and the error may increase with the ratio of the perimeter length to the area.

Areal measurements will affect statements about current density, but they also directly affect EQE calculations when a luminance meter or a spectroradiometer is used to determine OLED optical power. The calculation of EQE based on a spectroradiometer is usually based on the assumption that luminance is uniform over the entire OLED surface. If the area of an OLED is actually smaller than the assumed area, the optical power calculated will be overestimated because the optical power is calculated based on the area of the device times the luminance or radiance at a spot within the OLED active area.

3. Electronic Errors

The number of electronic errors is smaller than other errors because current and voltage measurements are routine, but there are a few considerations that one should keep in mind. One consideration, mentioned previously, is the area of the device.

Another consideration is an OLED is almost always in series with a resistor during testing. The DUT is only between the OLED active areas of the cathode and anode. One must be mindful to subtract voltage losses in poor conductors that are in series with the device such as indium-tin-oxide (ITO). Figure 1 shows a situation where there is ITO between the device active area and contact probes that connect the device to a power source. The ITO resistance outside the active area of the device should not be included in the measurements such as operating voltage of the device.

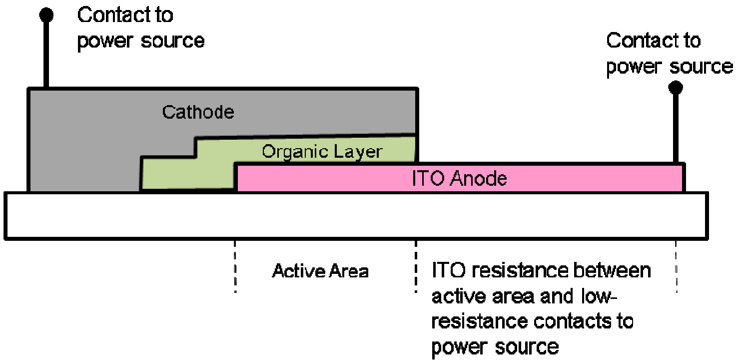

Figure 1 The ITO resistance between the active area and contact to the power source should be removed from measurements concerning only the device under test which is in the active area shown above.

A 0.1V error becomes increasingly important as devices become more efficient and as operating voltages are pushed to the thermodynamic limits [12], which are below 3V. For example, a 1mm^2 device operating at 100mA/cm^2 (or 1 mA/mm^2) has 1mA of current flowing through it and any series resistor. ITO is about 15 Ohm/sq. and 4 squares will make a 30 ohm resistor which will have a 30mV drop across it when an OLED is operating at 1 mA; therefore, errors on the order of 1-3% may be expected for devices with low operational voltage. Large area devices will have more lead losses because more current is required to operate a large device.

Another error is incurred due to RC time constants in measurement equipment. Essentially, voltage, current, and luminance are not stabilized before measurements are recorded when voltage or current is quickly increased; hence, there may be variations in calculated values based on voltage, current, and luminance. In large area devices, the device should ideally be thermally stabilized to capture a consistent measurement because the junction temperature or temperature of the organics of an OLED may be several degrees above the ambient temperature.

For example, the junction temperature of an OLED operating at 10mA/cm^2 can be 5-10 K above the ambient temperature. One can estimate the temperature difference between the ambient and OLED organic layers by considering a device with an active area of 5mm^2 operating at 10V and built on 1mm thick glass, which has a thermal resistance of ~1000 K/W. The junction temperature is (0.05 cm^2 * 0.01 mA/cm^2 *10V*1000 K/W) 5K above ambient temperature, which is typically 25°C or room temperature. The LM79-08 standard takes thermal stabilization into account.

4. Optical Errors

There are many sources of optical errors. For example, intensity of emission should be recorded in the appropriate units. Some fluorimeters only provide counts for intensity and do not provide W/sr.m^2.nm or cd/m^2.nm, so the usage of appropriate units is important.

Optical errors are complicated by changes in emission patterns with drive voltage due to changes in the electron-hole recombination region width or position, or both. The assumption of Lambertian emission is not always appropriate because OLED emission intensity may not vary with the cosine of the viewing angle [13, 14]. For example, an OLED EQE was 8.4% based on the measured emission profile, but the EQE was 9.4%, for the same device, based on the assumption of a Lambertian profile [14].

Furthermore, a distinction between a Lambertian luminance pattern and a Lambertian radiance pattern is an important consideration. An OLED may have a Lambertian luminance pattern (measured in cd/m^2) because the color is shifting from blue to green while simultaneously the total photon emission is decreasing faster than the cosine of the viewing angle, so its radiance pattern (measured in $W/sr.m^2$) is not Lambertian. These angular color and intensity shift complications can give rise to errors if not properly accounted for during calculations.

The OLED surface often does not have uniform emission because of temperature variations across the OLED surface due to I^2R heating caused by ITO [15, 16]. Hot regions tend to have higher radiance than cooler regions because more current flows through the hot regions and the variation of radiance from the OLED edge to the OLED center can be as much as 10% as shown for a bottom emission devices in Ref. [15]. This variation in luminance across the active area of a device could produce an overestimate of the EQE if only the highest luminance across the active area were used in EQE calculations. Therefore, a measurement of the radiance in a hot region may substantially overestimate the total optical power emitted from an OLED, and confirmation of OLED emission uniformity across the surface is necessary to reduce this error. Typically, heating is less pronounced at low drive current densities, so luminance measurement at low current density may reduce errors due to heating.

The errors incurred when a planar silicon photodetector is used to measure optical power [6] should be carefully considered because a planar silicon photodetector's responsivity has an angular dependence. Also, the responsivity of a planar photodetector is typically calibrated for normal incident light. A planar photo detector is therefore useful in a goniometer that measures irradiance in the far field where normal incidence may be assumed. Assuming no other errors and Lambertian emission at 555 nm and based on the detector underfill quantum efficiency versus angle of incidence in Ref. [17], the optical power is underestimated by about 1-3% using a planar photodetector.

Hence, a cosine corrector, such as an integrating sphere, is used to randomize the light before it impinges on the silicon detector, and randomized light will ideally always impinge on the photodetector for any type of emission pattern from any source; hence, a silicon detector coupled to a cosine corrector is necessary to acquire optical power measurements more accurately and without assumptions about the emission pattern characteristics. Illuminance meters are common instruments that use a cosine correction lens.

Another source of error using a planar photodetector is reflections from the OLED substrate. Reflections between the OLED and the silicon detector will overestimate the amount of light because multiple reflections of light will be measured by the detector. A ray of light that reflects off the surface of a silicon detector should not be allowed to reflect back onto the surface photodetector and placing an OLED directly on photo detector enables this situation. Intuitively, any normally emitted light from a bottom emitting OLED should bounce between the OLED cathode and the silicon photodetector when the detector is near the OLED, and the reflections in the normal direction would lead to an overestimate of the optical power in the normal direction. The overall overestimate over all angles from this error depends on several parameters including the geometry of the components, a top or bottom or transparent device architecture, device size, optical index matching fluid and OLED cavity effects.

5. Discussion and Conclusion

It would not be surprising that the total error causing overestimates in some reported results exceeds 10-15%. These errors enabled assumptions that 100% internal quantum efficiency was achieved many years ago based on devices with near 20% EQE and theoretical considerations that placed an EQE limit (in the forward direction) at 20%. It is likely that near 100% internal quantum efficiencies are only recently (within the last 4 years) being achieved in devices which is, in part, driving reported EQE of phosphorescent OLEDs to 30%.

As an example, Tanaka et al. [18] assume that the internal quantum efficiency of an OLED containing fac tris(2-phenylpyridine)iridium [$Ir(ppy)_3$] doped at 8 wt.% into 4,4'-N,N'-dicarbazolylbiphenyl (CBP) is 100% to explain their device EQE result of 29% and to support their conclusion that 30% outcoupling efficiency is possible. Kawamura et al. [19] showed that $Ir(ppy)_3$ doped at 8 wt.% into CBP has a photoluminescent quantum efficiency of about 90%; hence, confusion is created by the results. For example, if Tanaka et al 100% internal quantum efficiency is incorrect, the estimated outcoupling efficiency exceeds 32%.

Each researcher will have constraints that favor one type of test method over another. Cross-calibration of results between two or more working groups is highly recommended but published data that is easily vetted by all industry participants would be useful to all. Measurement errors exist and the OLED community does not have an agency such as the National Renewal Energy Laboratory that provides trusted and consistent solar cell device characteristics. There are several independent private testing laboratories available for testing OLED device characteristics, and this is a step towards improved understanding of results and theory. These independent laboratories use the method supported by the Illuminating Engineering Society of North America in the LM-79-08 standard to measure light emitting diode power efficacy [9] using an integrating sphere.

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