IST- 004607

OLLA White Paper on the Necessity of Luminous Efficacy Measurement Standardisation of OLED Light Sources

OLLA White Paper

Editors	OLLA WP5 members
Version	3.0
Date of issue	25 September 2007
Dissemination Level	Public – Open for discussion

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1. Introduction

Artificial light is everywhere. It is used in a wide range from high flux general illumination to low energy signage application. The variety of light sources ranges from high power street lamps to tiny status indicators in electronic equipment. Each application has its best fitting lamp technology, but light design and engineering is always looking out for possibilities to make the light sources comparable. This is not always possible, since the various lamps offer different form factors enabling special design features. However, end customers are putting their focus on several key parameters such as efficiency, lifetime and colour quality and are keen to describe the properties of a new light source by just a few key figures. This is sufficient to emphasise the need of standardisation in the field of measuring important light parameters for OLEDs as a new technology.
Considering the fact that 19% of the worldwide energy consumption is covered by light generation, there is a clear demand that all lighting technologies have to reach out for good and better efficiency. The efficiency of the transformation of electrical energy into light is one of the crucial parameters for lighting applications. Whilst conventional lamp technologies have already derived standards on the measurement of lighting efficiency, the field is still open for OLED light sources. Many definitions can be used to describe various efficiency or efficacy parameters and at least the same amount of measurement setups.

The OLLA project – an Integrated Project with 24 consortium partners funded under the 6th Framework Programme of the European Commission – has set its goal to realise a high brightness, high efficiency flat light source component for use in ICT and next generation lighting applications. It was realised by the partners quite soon that the publication of efficiency characteristics in the OLED community was not following a common rule. This is probably due to the fact that OLED technology in the beginning was not considered to result in real light sources, but was assumed to be restricted to display applications.

This White Paper tries to give indications which parameters are important when the luminous efficacy of a flat OLED light source is determined in a standardised procedure.

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2. Definitions

There are a lot of quantities in electro-optics which refer in a certain way to the efficiency of a light source. The first step to approach efficiency is the introduction of the external quantum efficiency which is given in equation (1).
Simply speaking, the external quantum efficiency η_{ext} is the ratio of extracted photons to injected charge carriers, but it is composed of different portions.

$$\eta_{ext} = b_1 * \eta_{recomb} * \eta_{opt} \qquad (1)$$

b_1 is the charge carrier balance of injected electrons and holes, which should be ideally 1, but can be lower due to different electron and hole mobilities in the organic layers. The recombination efficiency η_{recomb} is one of the key quantities to determine the external quantum efficiency. It determines how many excitons decay under the radiation of light in relation to the injected charge carriers. The last contributor is the optical outcoupling efficiency η_{opt}. It determines which portion of the generated photons can actually leave the device and are not e.g. trapped in high index layers of the OLED device.
If multiplied with 100% the external quantum efficiency can also be stated as a percentage. The formula above is just describing the OLED diode characteristics by counting photons and charge carriers, and it is not considering any electrical effects like contact resistances and other system aspects.

Macroscopically, the external quantum efficiency is strongly linked to the radiant efficiency of the light source η_e , i.e. the ratio between the radiant power $\Phi_{e\lambda}$ emitted by the device in the visible region and the electrical power P fed into the device. This is shown in equation (2), where λ denotes the wavelength of the photons and $\Phi_{e\lambda}$ the spectral radiant power. The visible region is typically defined between 380 and 780 nm.

$$\eta_e = \frac{\int_{\lambda_1}^{\lambda_2} \Phi_{e\lambda} * d\lambda}{P} \qquad (2)$$

In research, this quantity is of reasonable interest. It gives an indication how much still can be done to improve the extraction efficiency to an optimum value. Also the internal quantum efficiency – equation (1) without the optical outcoupling term – highlights the potentials which are still buried in the field of optical outcoupling. Forrest et al. [1] propose two measurement setups where this comparison can be performed easily.

However, OLEDs should finally be sold into products – into final applications. The lighting product community is consequently checking some key parameters in order to judge the quality of a light source. The crucial point here is that the visible light needs to be quantified, i.e. photometric characteristics are of higher interest than radiometric ones. Unfortunately, one of the most important parameters is known and used under different names (there are also slightly different understandings in definition) such as luminous efficiency, luminous efficacy or power efficiency. The "International Dictionary of Lighting Vocabulary" [2] defines the wording of the relevant expressions in four different languages (English, French, German, Russian). Thus, this paper will use the correct expression luminous efficacy η of the source for the ratio of the luminous flux Φ produced by the lamp and the electrical input power P. This must not be mixed up with the luminous efficacy of radiation which is the quotient of luminous flux Φ and radiant flux Φ_e.

$$\eta = \frac{\Phi}{P} = K_m * \frac{\int_{380\,nm}^{780\,nm} \Phi_{e\lambda} * V(\lambda) * d\lambda}{P} \qquad (3)$$

Equation (3) describes the luminous efficacy [3]. The spectral radiant flux $\Phi_{e\lambda}$ is weighted by the normalised spectral luminosity distribution function $V(\lambda)$ in the visible region between 380 and 780 nm. K_m denotes the maximum photometric radiant equivalent and equals 683 lm/W. Consequently, the unit of the luminous efficacy is lm/W.

3. How to measure OLED luminous efficacy?

3.1 General setup

The quantity “luminous efficacy” usually refers to the total luminous flux produced by the lamp. A typical OLED lamp is based on a transparent substrate with a plain surface. The substrate consists typically of a higher refractive index material (compared to air) which leads to reduced light outcoupling. Various structures can be placed onto the surface in order to enhance light extraction [4] [5]. The enhancement is significant, thus the outcoupling structures should be considered as part of the OLED lamp when the luminous efficacy is measured. However, this does not mean the use of a macroscopic half lens (diameter bigger than OLED device dimensions) or a macroextractor. Such extraction tools will never be used in an application because they put unacceptable limits to valuable OLED features such as flatness and light weight.

The main portion of extracted light is emitted via the substrate surface, though a small percentage is also coupled out via the substrate edges. This small portion is basically useless or lost in any kind of lighting application unless complicated light guide scenarios are realised to exploit this light as well. Considering the potential applications and products it makes sense to measure just the part of the luminous flux which can be finally “seen”.

OLEDs are often claimed to be Lambertian emitters, which is usually a valid approximation. For a non-structured substrate surface, the emission profile usually deviates not significantly from an ideal Lambertian one. However, by introducing outcoupling structures the profiles can be drastically changed. Thus, it is not correct to derive the luminous flux of an OLED device from a standard luminance measurement in perpendicular direction and extrapolating the result to the whole solid angle. The specific angular dependent emission profile must not be neglected. Another issue in using luminance measurements is the potential in-homogeneity of an OLED device. If the luminance was measured only on a small spot, important influencing factors would be neglected.
Consequently, the measurement of the luminous flux should be correctly carried out by the use of an integrating sphere. A possible setup is shown in Figure 1.

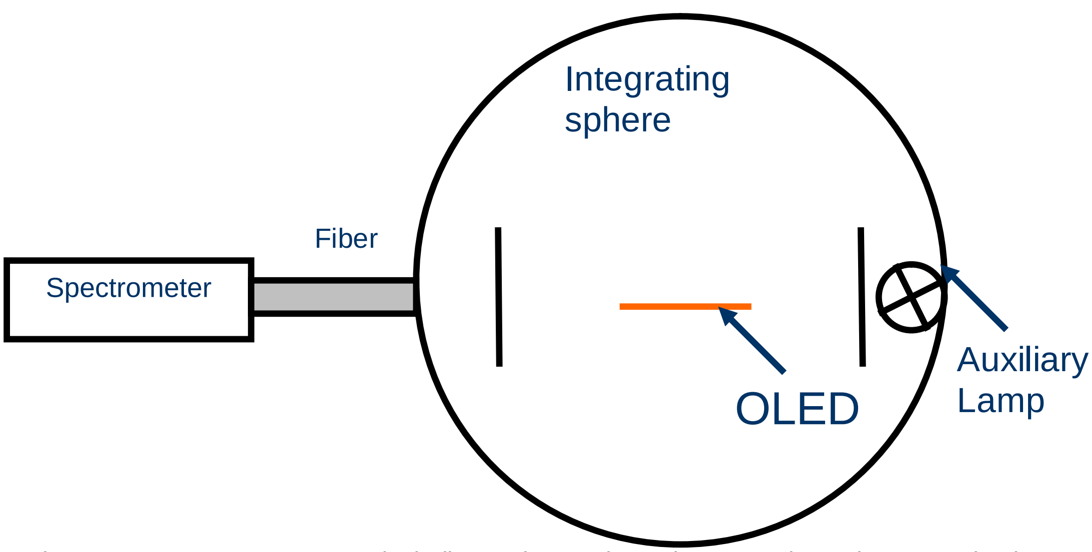

Figure 1: Measurement setup – including an integrating sphere – to determine OLED luminous efficacy. The auxiliary lamp is for calibration purpose to determine the absorption impact of the OLED body in the sphere. The shutters should prevent direct light incident on the detector of the spectrometer.

Another important issue is the edge emission of OLEDs. For other lamp technologies in general illumination applications there is a clear discrepancy between the luminous efficacy of the light source and the luminous efficacy of a the luminaire, i.e. the usable luminous flux in a luminaire system dived by the electrical input power. Just as an example, fluorescent lamps may reach 70 to 100 lm/W luminous efficacy (dependent on colour temperature), but in a luminaire installation, e.g. for office illumination, this value is easily decreased by 30% or even more. This is due to the use of inefficient reflectors and lamellas. The OLED lamp as a large area, flat light source bears already a high degree of final luminaire characteristics. By suppressing the emission via the substrate edges, the OLED technology is able to offer a practically relevant value of luminous efficacy which can be nearly completely transferred to each kind of luminaire design. The use of a black tape is recommended to prevent light leakage from the edges.

When performing a measurement inside an integrating sphere, the active area dimension of the OLED shall be at least 2 times smaller than the diameter of the integrating sphere [6]. However, the bigger the sphere diameter is in comparison to the light source dimension, the better the accuracy of the measurement.

The absorption of the OLED holder should be determined before a measurement is performed. This is done by measuring the sphere when illuminated by the auxiliary lamp, in a first run without and in a second run with the OLED body inside the sphere. The OLED is switched off during this measurement, the difference in the two measurement runs determines the impact of absorption of the OLED body. Furthermore the dark signal of the spectrometer (i.e. the spectrometer signal without any illumination) should be measured before the OLED measurement and subtracted from the measured signal.

Before starting the measurement, the OLED should reach an equilibrium state. After switching on the OLED, there may be a self heating effect (dependent on the efficacy and brightness) which has a significant impact on the electro-optic characteristics. This must be considered by introducing a waiting period of at minimum 1 minute between switch on and measurement start.

3.2 Operating parameters

In order to make OLED luminous efficacy measurements at different laboratories and locations comparable, it is highly important to report several operating parameters. These parameters are listed in the following.

If there are outcoupling structures used, this should be reported. Digital information is sufficient, the special type of outcoupling structure is not necessary to mention. A half sphere lens or macroextractor is prohibited to use.

It must be reported whether the edge emission was suppressed by means of a black tape. For transparent OLEDs, the emission to both main sides must be measured.

The operating current must be reported, preferably under constant DC drive conditions. The operating current should be chosen in that way that the resulting luminance in forward direction is in the range of 1000 to 2000 cd/m². This luminance range covers a broad range of lighting applications. Deviations must be reported.
If a special wave form is applied for driving, duty cycle, amplitude and average value over time must be reported.

The size of the active lighting area must be mentioned. Also the diameter of the integrating sphere and the longest extension of the OLED must be mentioned. This gives an indication of the measurement accuracy. The measurement error should be mentioned as well.

The operating voltage or the electrical input power must be reported, preferably both values.

The resulting luminous flux needs to be reported as absolute value.

Also, the ambient temperature should be reported.

Furthermore, information on the colour temperature should be provided. In case of white colour the colour temperature should only be given, if a CRI can be determined, i.e. the CIE coordinates are within Planck corridor. If this is not applicable, just the CIE coordinates should be mentioned.

Finally, the luminous efficacy can be calculated.

4. Conclusion

For a standardised measurement of the OLED efficacy it is essential to record and report certain parameters in order to make results comparable. These parameters are summarised in Table 1:

Parameter	**Unit**
Operating Current (average)	A
Voltage	V
Waveform, if applicable	DC / AC (duty cycle, amplitude)
Electrical input power	W
Active Lighting Area	m^2
Outcoupling Enhancement Structure	Yes / No
Luminous flux	lm
Luminous efficacy	lm/W
Colour Temperature (for white); CIE coordinates	K
Ambient Temperature	°C

Table 1: Summary of parameters to be documented for a standardised OLED luminous efficacy measurement

The partners of the OLLA project highly recommend to follow the above described measurement setup and procedure in order to ensure reliable judgement of data originating from different laboratories. This procedure reflects already the characterisation needs with regard to real OLED lighting products and applications.

5. References

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