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A simple method for the photometric characterization of organic light-emitting diodes

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ABSTRACT

A simple method for the photometric characterization of organic light-emitting diodes (OLEDs) is reported. It is based on the indirect measurement of the total emitted optical power by using a calibrated photodiode and the optical emission spectrum and space emission diagram of the OLED. From this and by measuring the current–voltage characteristic of the OLED all the relevant radiometric and photometric quantities can be extracted, including the external quantum efficiency. The usual method to collect all photons emitted by a LED source in the half space uses an integrating sphere with the LED source placed at the entrance hole and a photodiode (PD) placed at an exit hole at some point on the sphere surface. Here we show that the same result can be also achieved in free space by a simple geometrical arrangement of the PD in respect of the OLED source, with no need of an integrating sphere. Moreover, we find that a large area photodiode placed in contact with the OLED surface measure about 82% of the total emitted power.

1. Introduction

External quantum efficiency (EQE) of organic light-emitting diodes (OLEDs) [1] is one of the most important parameters for devices assessment and for comparing OLEDs performance. The EQE is the ratio of the total number of photons emitted by the OLED in all directions to the number of injected electrons.

The key point for the radiometric characterization is to measure the total optical power P_0 emitted by the OLED in the half space (i.e., the emitted light that is waveguided by the glass substrate is not accounted for) considering that an LED is a polychromatic light source with a certain spatial emission pattern. P_0 can be measured using a large area calibrated Si photodiode (PD) of known responsivity (W/A) placed in contact with the OLED surface [2]. This requires the measurement of the PD photocurrent, together with the OLED emission spectrum to calculate the "equivalent" responsivity of the PD, as explained in Appendix A. The photometric quantities such as luminous efficiency (cd/A) and luminous power efficiency (lm/W) can be calculated using the photopic visibility curve and the OLED emission spectrum [3], as explained in Appendix B.

A calibrated Si PD is meant to be used for normal incidence of the light beam. In fact, the reflectance of both the Si surface and the PD glass window increases for obliquely incident rays and moreover the OLED emits photons in a range of angular directions. This means that with the PD placed in contact with the OLED surface [2] one measures an emitted power that is less than P_0 but more than the power emitted by the OLED in the normal direction to its surface.

Here we present a simple geometrical modification of this method, where the PD with radius r_{PD} is placed on axis at a distance d_{PD} from the OLED with radius r_{OLED}, as shown in Fig. 1(a), where a radial symmetry in the source plane is assumed and a circular PD is used.

If $d_{PD} \gg (r_{PD}, r_{OLED})$, then the PD "sees" the OLED as a point source and far field approximation with normal incidence of optical rays on the whole PD surface holds true. In this condition, and accounting for the OLED spatial emission pattern I(θ), the power P_{PD} impinging on the PD area is simply related to P_0 by:

$$\mathbf{f} = \frac{\mathbf{P_{PD}}}{\mathbf{P_0}} = \frac{\int_0^{\theta_{PD}} \mathbf{I}(\theta)\mathbf{d}\theta}{\int_0^{\pi/2} \mathbf{I}(\theta)\mathbf{d}\theta} = \mathbf{sin}^2\left(\mathbf{arctg}\frac{\mathbf{r_{PD}}}{\mathbf{d_{PD}}}\right), \quad (1)$$

where the last equality holds for a Lambertian source for which $I(\theta) = I_0\cos(\theta)$, where I_0 is the intensity in the normal direction to the OLED surface and the angle θ identifies the direction with respect to the normal. This is a very good approximation for a bilayer tris (8

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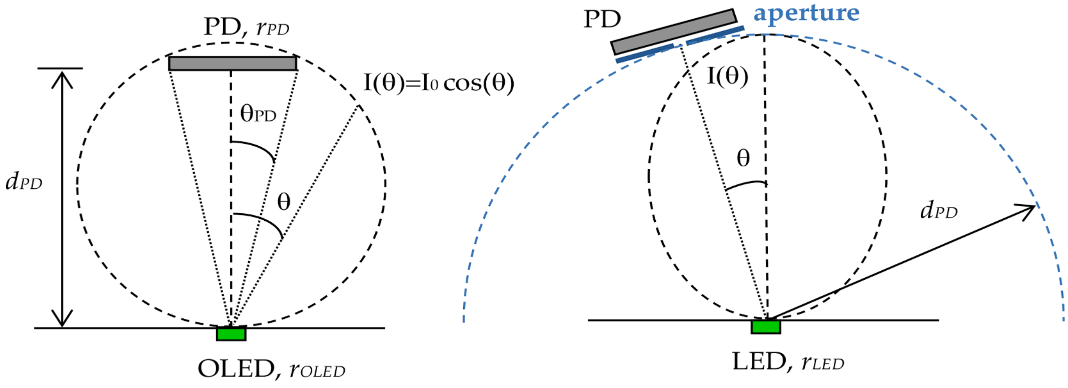
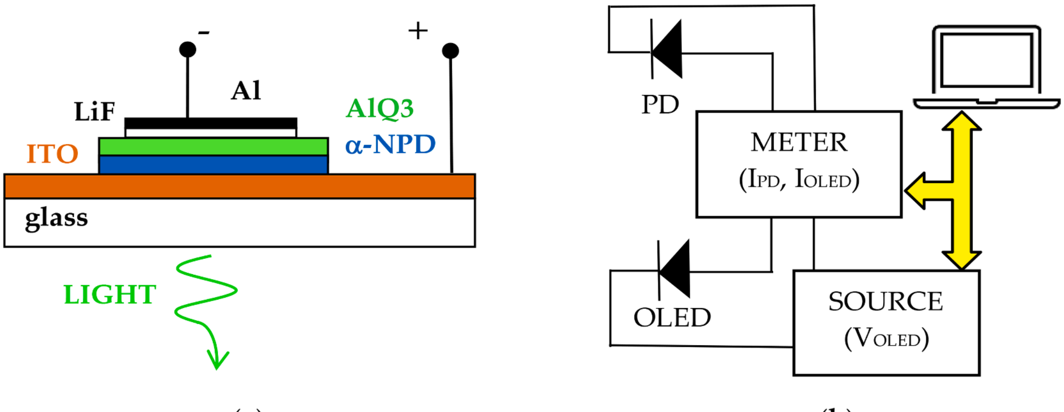


(a) **(b)**

Fig. 1. Geometrical arrangement of the measurement setup: **(a)** Lambertian OLED or chip LED with the PD placed along the normal direction to the OLED surface, **(b)** measurement of the spatial emission pattern of a non-Lambertian LED by changing the angle θ and keeping d_{PD} constant.



(a) **(b)**

Fig. 2. **(a)** AlQ3-based bilayer OLED structure; **(b)** schematic of the automated voltage source (V_{OLED}) – current meter (I_{OLED}, I_{PD}) system.

idroxyquinoline) aluminum (AlQ3)-based OLED with negligible microcavity effects [4,5] and for a chip LED as well. From equation (1) one gets:

$$\mathbf{P}_0 = \frac{\mathbf{P}_{\mathbf{PD}}}{\mathbf{f}} \tag{2}$$

We notice that the correction factor f as given by equation (1) is <1 and dependent on the distance d_{PD} and the PD radius r_{PD}. For this reason, it is important to establish the minimum distance d_{PD} for the method to be valid. To this aim a practical criterion is $d_{PD} \geq 10$ (r_{PD}, r_{OLED}).

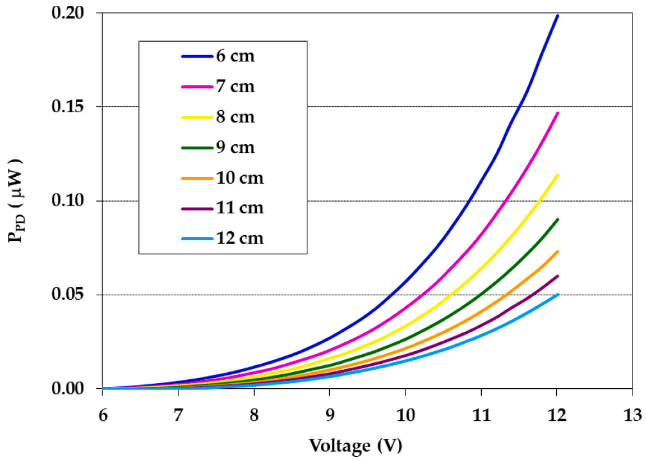


Fig. 3. Optical power measured by the PD vs. the OLED voltage V_{OLED} with the OLED-PD distance d_{PD} as parameter.

If the angular emission pattern has radial symmetry in the source horizontal plane it is simple to measure the spatial emission pattern I(θ) in the vertical plane. Hence the method can be easily extended to a non-Lambertian LED source. This can be done by the slightly modified geometrical arrangement shown in Fig. 1(b), where the PD is moved on a half-circle with radius d_{PD} i.e., only the angle θ is changed in discrete steps. Again $d_{PD} \gg r_{LED}$ and the Si PD is used with an aperture in front of it to increase the spatial accuracy of the emission pattern measurement.

As an alternative the photodiode can be kept fixed, and the LED source is rotated in respect to its center in the half space. This last approach can be used for the measurement of LED sources with arbitrary spatial emission pattern but in this case the use of an integrating sphere can be more convenient and less time consuming. We notice that a commercial apparatus called goniophotometer exists for the measurement of the intensity emitted from an optical source at different angles, i.e. its angular emission diagram.

2. Materials and methods

The OLEDs used for this work are fabricated by vacuum thermal evaporation on glass substrates pre-coated with an Indium Tin Oxide film. The emitting area is 3 mm^2 i.e., $r_{OLED} = 0.97$ mm. AlQ3 is used as the electron transport and emission layer and N,N0 di(naphthalene-1-yl)-N,N0-diphenylbenzidine (NPB) as the hole transport layer. The cathode consists of 1 nm of LiF followed by 100 nm of Aluminum. The complete structure is shown in Fig. 2(a). Full fabrication details are

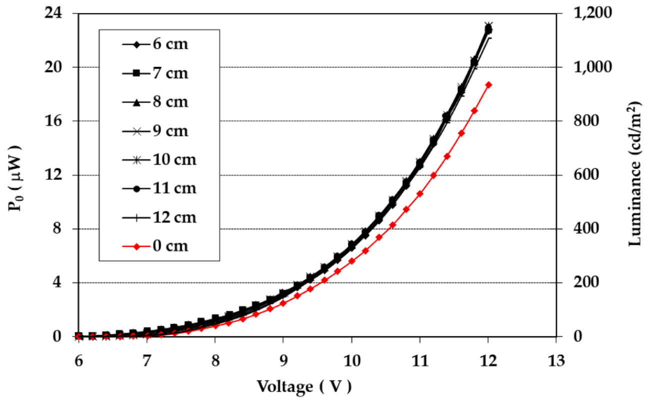


Fig. 4. Calculated total optical power P_0 vs. the OLED voltage V_{OLED} with the OLED-PD distance d_{PD} as parameter. The curve for $d_{PD} = 0$ cm is the power directly measured with the PD in contact with the OLED surface. The corresponding calculated luminance is on the right axis.

reported in Cusumano [6]. All measurements are made on not-encapsulated devices in air immediately after vacuum deposition.

A calibrated Si PD (NEWPORT 808-UV with 100 mm^2 area, i.e. $r_{PD} =$ 5.6 mm) is used to measure the emitted optical power through the PD photocurrent, its calibrated responsivity curve and the OLED emission (electroluminescence) spectrum, as explained in the Appendix A. The emission spectrum is measured with a fiber spectrometer (Ocean Optics USB-2000). The current–voltage characteristics of the OLEDs and the PD photocurrent are measured in the dark by a custom automated voltage source (V_{OLED}) – current meter (I_{OLED}, I_{PD}) system, as depicted schematically in Fig. 2(b). To measure current a virtual ground configuration is used inside the meter box together with a precision current-to-voltage converter.

3. Results and discussion

To assess the minimum distance d_{DP} for the method validity, first we measured P_{PD} vs. OLED voltage V_{OLED} varying d_{PD} from 6 cm to 12 cm with 1 cm step, as shown in Fig. 3. At the μW scale of the P_{PD} axis the emitted power for $V_{OLED} < 6$ V is negligibly small, hence it is not shown in the plot. The minimum distance $d_{PD} = 6$ cm is already greater than ten times $r_{PD} = 5.6$ mm. It can be notice that P_{PD} decreases with increasing d_{PD}. Then the total emitted power P_0 is calculated using the correction factors f given by (1).

The result is plotted vs. V_{OLED} in Fig. 4 together with the case $d_{DP} = 0$ cm i.e., the PD placed in contact with the OLED surface. The corresponding luminance, calculated from the power using the photopic visibility curve and the OLED emission spectrum, as explained in the Appendix B, is shown in the secondary axis of the plot. It can be noticed that, for the range of chosen d_{PD} distances, the calculated P_0 values are essentially the same. Therefore, we infer that $d_{PD} = 6$ cm is already sufficient for the method validity. As Fig. 4 shows, for $d_{PD} = 0$ cm i.e., with the PD placed in contact with the OLED surface the measured power is about 82% of the calculated P_0. The right axis of the Fig. 5 plot shows the luminance calculated from the power using the photopic visibility curve and the OLED emission spectrum [2].

The complete electrical and photometric characteristics of the OLED are shown in Fig. 5(a) where the linearity of the luminance vs current is evident. The maximum luminance reaches about 1,100 cd/m^2. The EQE (%) and power efficiency (lm/W) are shown in Fig. 5(b). The maximum EQE is about 0.6%.

4. Conclusions

The reported method for the photometric characterization of OLEDs is simple and advantageous because an integrating sphere is not needed. It can be easily extended to any LED source by measuring in advance its spatial emission pattern. We demonstrate that the optical power measured by a large area Si PD placed in contact with the OLED surface is 18% smaller than the calculated “true” total optical power P_0 emitted by the OLED in the half space.

The method is targeted to the calculation of the EQE of OLEDs. Moreover, it can be useful as a practical laboratory demonstration for engineering or physics students.

For comparison, a conventional spot spectroradiometer, such as Konica Minolta CS-2000, uses a lens optical system and basically a diffraction grating and a calibrated CCD sensor for the visible range 380–780 nm. The field of view (acceptance angle) of the instrument is limited to 1° or less and it is set and specified by the user together with the measuring area and the distance from the source. The spectral radiance (W/sr•m^2•nm), luminance (cd/m^2) and CIE coordinates (related to the emission spectrum of the source) are calculated by a specific software from geometrical parameters and the basic relationships and equations that link radiometric and photometric quantities. Of course, in the case of a Lambertian source such as an OLED the total emitted power (and hence the EQE) can also be calculated from the spectral radiance and CIE coordinates, with no need for an integrating sphere.

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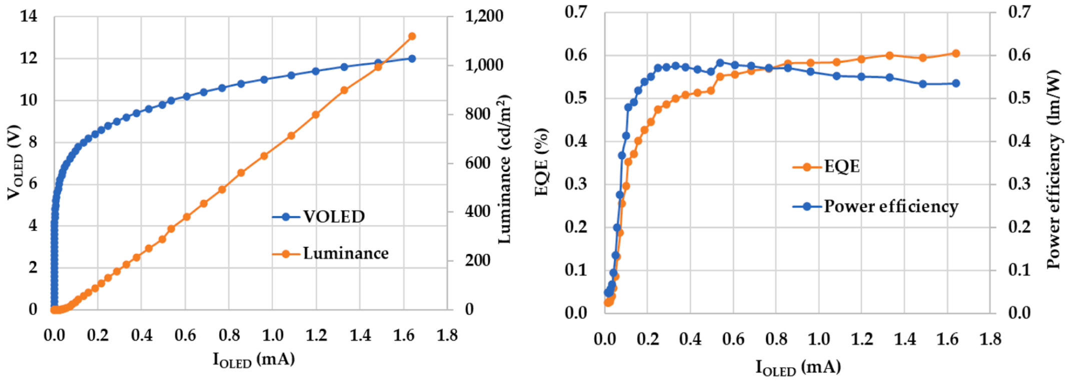

(a)

(b)

Fig. 5. **(a)** OLED voltage V_{OLED} and calculated luminance (secondary axis) vs. forward current I_{OLED}; (b) OLED external quantum efficiency and power efficiency vs. forward current I_{OLED}.

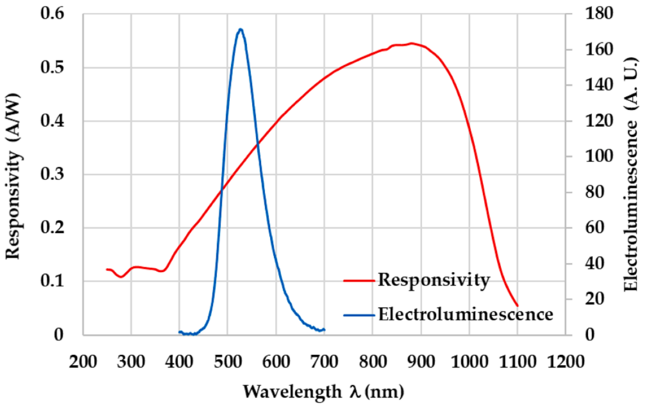

Fig. A1. Calibrated responsivity curve of NEWPORT 808-UV Si PD and electroluminescence spectrum of green emitting AlQ3-based OLED. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Conversion from PD photocurrent to optical power. The PD responsivity (A/W) is dependent on the wavelength λ of the incident light and is denoted as $R(\lambda)$. As the OLED is an incoherent (polychromatic) optical source we denote its emission spectrum, normalized in respect to the spectrum area, as $S(\lambda)$. Hence the normalization condition is:

$$\int_{\lambda_1}^{\lambda_2} S(\lambda)d\lambda = 1 \tag{A1}$$

where λ_1 and λ_2 are the extremes of the OLED emission spectrum. If P_{PD} is the power corresponding to the PD photocurrent I_{PD} then.

$$I_{PD} = \int_{\lambda_1}^{\lambda_2} P_{PD} R(\lambda) S(\lambda) d\lambda = P_{PD} \int_{\lambda_1}^{\lambda_2} R(\lambda) S(\lambda) d\lambda \tag{A2}$$

From (A2):

$$P_{PD} = \frac{I_{PD}}{\int_{\lambda_1}^{\lambda_2} R(\lambda) S(\lambda) d\lambda} = \frac{I_{PD}}{R_{eq}}. \tag{A3}$$

The denominator in (A3) is the “equivalent” responsivity R_{eq} of the PD for the considered OLED source. The electroluminescence spectrum, measured by a fiber spectrometer (Ocean Optics USB-2000), is shown in Fig. A1, together with the NEWPORT 808-UV Si PD calibrated responsivity curve provided by the manufacturer. Notice that the OLED maximum emission occurs at $\lambda_{peak} = 528$ nm corresponding to bright green. The R_{eq} calculation can be made by a spreadsheet or mathematical software using the measured data points. The result of the calculation in our case gives an equivalent responsivity $R_{eq} = 0.333$ A/W.

The EQE is a radiometric quantity defined as the ratio of externally emitted photons to injected electrons under forward bias and is usually expressed in %. Once the total emitted power P_0 is calculated using P_{PD} and the correction factor f as given by (1) the EQE can be expressed as:

$$EQE = \frac{P_0/E_{avg}}{I_{OLED}/q} \tag{A4}$$

where q is the electron charge and E_{avg} is the average photon energy. In a first order approximation E_{avg} is related to the wavelength of maximum emission λ_{peak} of the OLED by $E_{avg} = h\,c/\lambda_{peak}$, where h is the Planck constant and c the speed of light. Notice that P_0 in the equation (A4) is the optical power value, corresponding to each measured I_{OLED} value.

Appendix B

Conversion from radiometric to photometric quantities. Photometry measures the effect of visible radiation/light on the human eye by considering the photopic sensitivity curve $V(\lambda)$ [2]. This is a normalized bell-shaped curve (peak value = 1) vs. wavelength λ ranging from 380 nm to 770 nm that describes the sensitivity of the human eye for daylight vision. All radiometric (absolute) quantities are weighted by $V(\lambda)$ to give the corresponding photometric quantities [2].

As an example, we can briefly treat the calculation of the luminance from the optical power P_0. The luminous flux corresponding to a monochromatic radiation at λ with optical power P_0 is given by:

$$\Phi_e(\lambda) = K_m P_0 V(\lambda) \tag{B1}$$

where $K_m = 683$ [lm/W]. The luminous flux $\Phi_e(\lambda)$ is measured in lumen [lm]. If P_0 is due to an incoherent optical source with normalized emission spectrum S(λ), as stated by (A1), then $P_0(\lambda) = P_0\, S(\lambda)$ and the total luminous flux Φ_V is given by:

$$\Phi_V = \int_{380\text{ nm}}^{770\text{ nm}} \Phi_e(\lambda) d\lambda = K_m \int_{380\text{nm}}^{770\text{ nm}} P_0 S(\lambda) V(\lambda) d\lambda \tag{B2}$$

From the luminous flux Φ_V the luminous intensity I_V [cd = lm/sr] can be calculated. For a point source the result is [2]:

$$I_V = \frac{\Phi_V}{\pi} \tag{B3}$$

The OLED can be considered as a Lambertian point source if the PD is at a large distance compared to the OLED radius. In this case the luminance L_V [cd/m^2] is simply given by:

$$L_V = \frac{I_V}{A} = \frac{\Phi_V}{\pi A} \tag{B4}$$

where A is the OLED surface area, according to [2].

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