ISSN 0974 - 9373

Vol. 15(2011) Special Issue 2 **Journal of International Academy of Physical Sciences** pp. 231-238

Analytical Measurements for Quantum Efficiency of Organic Light Emitting Diodes*

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(Received June 14, 2011)

Abstract: Electroluminescence (EL) in organic displays and lighting devices has shown steady progress. The electronic devices based on organic semiconductors are expected to serve the society in near future where solid state lighting is an important example. In the present paper we have attempted, from the first principles, to provide an analytical approach for calculation of external quantum efficiency (*EQE*) of organic light emitting diodes (OLEDs). This approach requires only the EL spectrum and illumination versus current characteristics of the devices to calculate the *EQE*. In these calculations the light emission has been considered to be perfectly diffusive from the emission surface. The efficiencies calculated in this way have been compared with the actual values of the *EQE*s for the different OLED structures available in the literature. The calculated values have shown good agreement with the measured values.

Keywords: OLEDs, Quantum efficiency, Organic semiconductors.

1. Introduction

Organic semiconductors have emerged as truly powerful materials for electronic devices, where light emitting diodes (LEDs), solar cells, thin film transistors (TFTs) and lasers are some of the typical examples. Tang and Vanslyke in 1983 witnessed electroluminescence (EL) in organic molecules, which revived interest in organic EL devices[1]. Burrounges *et al.*[2] demonstrated, for the first time, EL in conjugated polymers. Since the advent of electroluminescent polymers, polymeric materials with emission spanning the broad spectrum of visible[3-9] and non-visible radiation (near infrared)[10] have been synthesized. Over the past decade there has been great progress in

*Paper presented in CONIAPS XIII at UPES, Dehradun during June 14-16, 2011.

these materials and devices towards their improved performance. Owing to the potential features e.g. thin, light weighted, large area and flexible device production at very low cost, the organic light emitting diodes (OLEDs) are capable to give a great competion to LEDs based on inorganic semiconductors, which are already available in the market and are used for various small applications. Various electronic devices e.g. CD player, MP3 player, video game, rajors, cameras, mobilies etc. consisting OLED based displays are now available in the market. Research is being done intensely for further improvement in the performance of these devices. Presently the focus is on the development of white LEDs based on organic semiconductors, which is now considered to be a strong candidate for general illumination purpose. Due to the fast and steady development, these devices are expected to serve the society in the near future.

Efficiency is a key issue for energy-consumption as well as for the longevity of the device, since the ability to operate the device at a lower input power at a given luminance reduces the heating and increases the device lifetime. To be widely adopted, thin film organic materials must possess a significant advantage in efficiency especially in low power, portable applications. Luminescence quantum efficiency is one of the most critical issues in the successful design of organic light emitting devices. High efficiency and long lifetime are essential for commercializing the OLEDs. In recent years, tremendous efforts have been directed at developing more efficient OLEDs, which employ low operating voltage and achieve high external quantum efficiency[11-13].

Quantum efficiency is an important parameter for OLEDs. However, quantum efficiency is difficult to measure precisely because one cannot completely collect and detect all the photons emitted from a given EL device. There are very few methods available to measure exact quantum efficiency and in most of these cases an integrating sphere and a monochromator are necessitated[14-17]. These methods are precise but difficult and big problems occur during measurements. The quantum efficiencies determined by such different measuring methods cannot be compared equivalently as the detailed procedures are not available. In this paper we present a very simple method of measuring the external quantum efficiency of OLEDs.

2. Theory

OLEDs are two electrodes systems where organic materials are sandwiched between them. Application of an external bias results into injection of electrons and holes from cathode and anode respectively that transport through the organics and recombine to produce photons. The transportation and recombination of electrons and holes in organics constitute a current. The internal quantum efficiency (η_{int}) of an OLED is defined as the the number of photons produced within the device (N_{in}) over the number of electrons injected ($N_{electron}$) per unit time, and can be given by

(1) $$\eta_{\text{int}} = \frac{N_{\text{int}}}{N_{electron}}.$$

In more detailed manner Eq. (1) can also be written as

(2) $$\eta_{\text{int}} = \gamma \eta_s \phi_f,$$

where γ is a fraction of injected charges that produce excitons and called charge balance factor, η_{s} is the fraction of singlet excitons called singlet exciton efficiency and ϕ_f is the fraction of energy released from material as light and called quantum efficiency of fluorescence. On the other hand the external quantum efficiency is nothing but the emitting photons coming out of the device (N_{ext}) per unit injected electrons per unit time and can be written as

(3) $$\eta_{ext} = \frac{N_{ext}}{N_{electron}}.$$

The internal quantum efficiency can be related to the external quantum efficiency as

(4) $$\eta_{ext} = R_e \eta_{\text{int}},$$

where R_{e} is the extraction or out-coupling efficiency representing the number of photons coming out of the device per unit photons generated in the device.

Since it is very difficult to measure the internal quantum efficiency and the out-coupling coefficient, the external quantum efficiency is very difficult to calculate. We therefore now present a simple method to calculate the external quantum efficiency of an OLED device. We can calculate the external quantum efficiency by just measuring the emission pattern and brightness of the device. The number of photons can just be calculated by emission spectrum. As the emission pattern gives the relative intensity or number of photons of different energy, corresponding to different wavelength. If the total intensity of the emitted light is known the efficiency can be calculated in the following way.

The number of photons emitted at a wavelengths λ with optical power of 1 lumen can be given by

(5) $$N_{photon}(\lambda) = \frac{\lambda}{683.K(\lambda).hc}.$$

where $K(\lambda)$ is the Commision international de l'Eclairage (CIE) standard photopic efficiency function. If $L(\lambda)$ is luminance of the device at wavelength λ the luminous flux will then be given by

(6) $$\phi(\lambda) = \pi.L(\lambda).$$

Therefore the number of photons emitted by the device at λ will now be given by

(7) $$N_{photon}(\lambda) = \pi.\frac{L(\lambda).\lambda}{683.K(\lambda).hc}.$$

Now the total number of photons emitted and received externally of the device will now be given by

(8) $$N_{ext} = \int_{380}^{780} N_{photon}(\lambda)\, d\lambda.$$

Note that we have considered only the photons emitted in the visible region. Since the luminescence is directly proportional to the emission intensity I(λ), L(λ) can be written as L(λ) = α K(λ)I(λ) where α is a constant. Now the total number of external photons will be given by

(9) $$N_{ext}(\lambda) = \int_{380}^{780} \frac{\pi.\alpha.I(\lambda).\lambda}{683.hc} d\lambda.$$

Since $L(\lambda)$ is luminance of the device at wavelength λ the total luminescence (L_{total}) of the device will be

(10) $$L_{total} = \int_{380}^{780} L(\lambda) d\lambda,$$

or

(11) $$L_{total} = \alpha \int_{380}^{780} I(\lambda).K(\lambda) d\lambda\, ,$$

L_{total} can be obtained experimentally by taking measurement from the front of the OLED device using a luminance meter and the values of $I(\lambda)$ by measuring the EL spectrum. Now Eq. (11) can be used to get the value of α. Now substituting the calculated value of α in Eq. (9) the external number of photons can be calculated. The number of electrons injected into the device can easily be obtained from the current through the device. Once the number of injected electrons and the photons received out of the device are known the external quantum efficiency of the device can easily be calculated using Eq. (3). This method enables the quantum efficiency to be determined from the conventionally measured luminance-current characteristics and the emission spectrum. There is no need of special and expensive equipments. Calculation of the equations can be carried out using an ordinary computer.

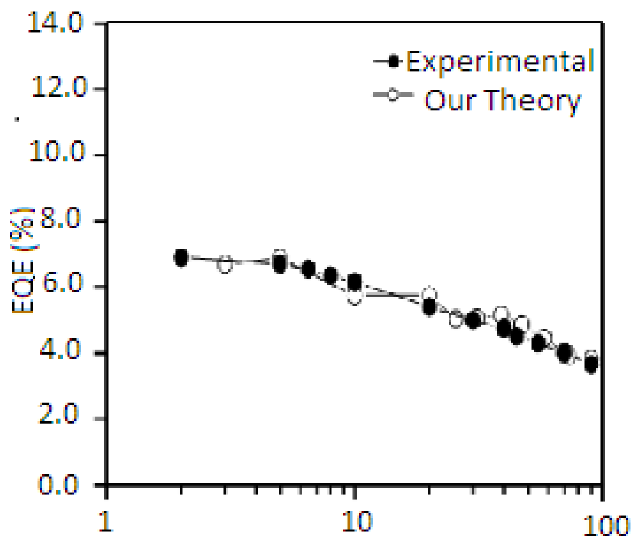
3. Comparison with Experimental Observations

It is now clear from the theory presented above that only by measuring the EL spectrum and the current-luminescence characteristics we can easily calculate the external quantum efficiency of an OLED. We now present the comparison of our theory with the experimental data available in the literature. We have digitized the EL intensity at different wavelengths from EL spectrum and the luminescence at different current density from the luminescence vs current characteristics of a number of papers available in the literature and the comparison is given below.

Suzuki et al.[18] reported a highly efficient OLED based on the co-polymers consisting bis(2-phenylpyridine)iridium (acetylacetonate) [Ir(ppy)$_2$ (acac)], *N*, *N*'-diphenyl-*N*, *N*' – bis (3-methylphenyl) - [1, 1'-biphenyl] -4,4'-diamine (TPD) and 2-(4-biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole (PBD) as the side groups. The phosphorescent unit was functionalized with a styrene group, and the other units were vinylated by a common acetylation-dehydration procedure. The co-polymers were synthesized with different ration of Ir(ppy)$_2$(acac), TPD and PBD units. We compare our theory with the experimental data of the LED based on the polymer consisting Ir(ppy)$_2$(acac), TPD and PBD in 3:18:79 ratio with Ca as the electron injection layer. Fig. 1 shows the comparison of EQE measured by Suzuki *et al.* [18] for the above mentioned polymer, with our theory. We used the EL spectrum, current-voltage (*J-V*) and luminescence-voltage (*L-V*) characteristics to calculate the EQE. A good agreement can clearly be seen between the measured data of Suzuki *et al.* and our theory.

We now compare our theory with the experimental data reported by Baldo *et al.*[19] and the results are shown in Fig. 2. A good agreement of our theory with the data reported by Baldo *et al.* can also be seen clearly.

Fig. 3 compares our theory with the data reported by Li *et al.*[20]. They reported a green organic light emitting diode. The LEDs were prepared in single layer and multilayer configurations. We compared our theory with the data reported for multilayer LED. We used the data of EL spectrum, efficiency vs current density characteristic and luminescence vs voltage characteristic to calculate the experimental quantum efficiency of the multilayer polymer LED. It is noted that the calculated values are near to the experimentally reported values. Thus, one can obtain the approximate experimental quantum efficiency using this method. The little discrepancy in the data reported in the papers discussed above and calculated by us using the theory presented above can be attributed to the error occurred during the digitization of the reported data.



Current Density (mA/cm^2)

Fig. 1. Comparison of EQEs at different current densities measured by Suzuki *et al.*[18] for a OLED and that calculated by the theory presented by us

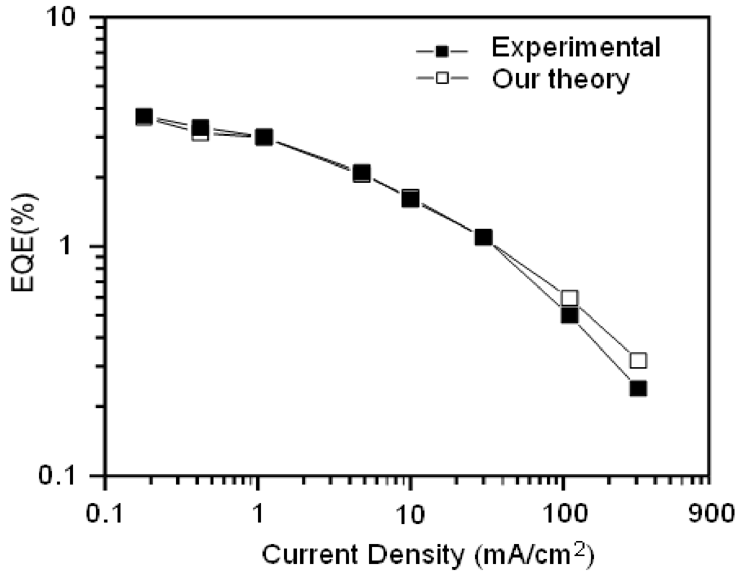


Fig. 2. Comparison of EQEs at different current densities measured by Baldo *et al.*[19] for a OLED and that calculated by the theory presented by us

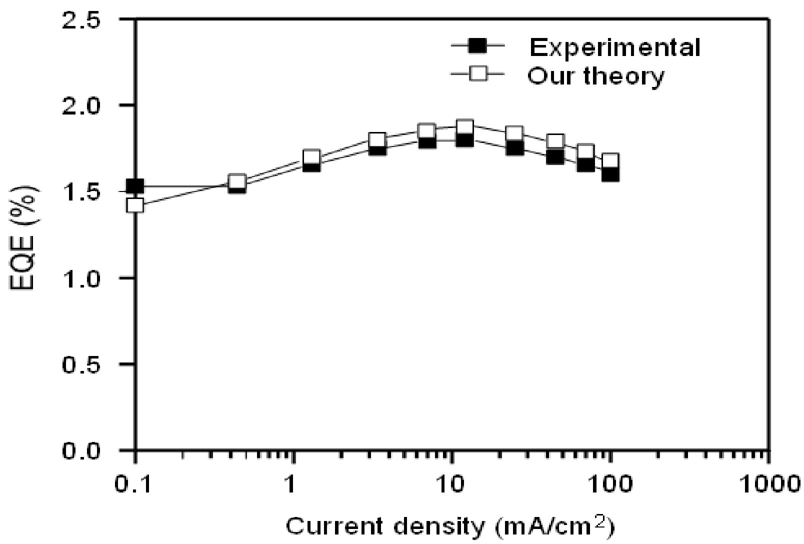


Fig. 3. Comparison of EQEs at different current densities measured by Li *et al.*[20] for a multilayer OLED and that calculated by the theory presented by us

4. Conclusion

We have developed a method to estimate the external quantum efficiency of OLEDs and the method is further verified in light of published literatures. It is verified that the calculated values are in accord with the reported measurements. In this method, the photons emitted from the device are detected but the photons from the back and sides of the device are not. This yields an error from the true value of the external quantum efficiency. The accuracy of the luminance meter can also yield an error. However, for display applications, the photons from the front of the display panel are used. Thus, the front efficiency by this method can be applied to the evaluation of device performance.

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