Measuring the Efficiency of Organic Light-Emitting Devices**

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Organic light-emitting devices (OLEDs) are emerging from the stage of being a research curiosity to that of becoming a practical appliance with important commercial applications, especially with respect to displays for mobile information devices. As in all emerging technologies, standards of measurement have developed in an ad hoc fashion, with laboratories applying different techniques to measure important performance parameters of the devices or materials under investigation. While a technology is in its early stages, the apparent discrepancies that arise from different measurement methodologies have little significant influence on the progress of the research. However, as the field matures, practical standards must be put in place such that accurate and consistent measurements can be taken at several laboratories at distributed locations and times. This provides a basis for the valid comparison of different device and material properties, thereby helping to clearly identify real advances.

In the case of OLEDs, there appear to be several different, and sometimes contradictory methods for measuring quantum efficiency and device reliability. Here, we seek to clarify the differences and to discuss "best methods" for measuring and quoting device efficiency. If these procedures are adopted by the scientific community, then standards can be maintained between various laboratories that will be easily interpreted and compared to other work emerging in the field.

There are two prevailing philosophies that are followed in characterizing OLEDs. The first is an engineering approach that simply recognizes the OLED as a display device, and thus utilizes standard instruments developed to characterize other, more technologically evolved displays such as liquid crystal displays. While this approach allows for straightforward comparison of OLED performance with other technologies, it runs the danger of missing important underlying differences in device physics and offers little help in understanding how best to develop a rational design for new materials and device structures. The second approach uses physical measurement techniques that are less routine and subject to more laboratory-to-laboratory variation. We discuss both approaches below and suggest how the second approach may be made more routine and hence better suited to applications in a standardized way.

The primary complication introduced by a display device is that the eye response, described by the *photopic* (light-adapted) luminous efficacy, must be taken into account. This represents the photosensitivity of a "standard" human eye (see Fig. 1). The eye response-weighted equivalents (i.e., the photometric equivalents) of the radiometric quantities[1,2] of radiance [W/sr m^2], radiant efficiency [W/sr A], and power (or "wall plug") efficiency [W/W] are then luminance (in *candelas per meter squared* [cd/m^2]), luminous efficiency [cd/A], and luminous power efficiency, or luminosity (in *lumens per watt* [lm/W]). The photometric quantities are used to describe the properties of a display.

In addition to the complications arising from the application of OLEDs to displays, the OLED itself forms a complex optical cavity whose emission properties can depend strongly on viewing angle. A typical OLED is comprised of a stack of organic and inorganic layers, each layer with a different complex index of refraction, thereby forming a weak microcavity.[3] This stacked structure introduces significant interference effects that modulate the device efficiency and the emission spectrum and modify the emission pattern from that of an ideal Lambertian emitter. A Lambertian emitter is isotropic, emitting with equal radiance into any solid angle within the forward "viewing" hemisphere. We will now consider the effects of viewing angle, eye response, and other factors relating to accurate quantification of OLED efficiency.

1. Definitions

To begin, we define the various efficiencies employed in evaluating the fundamental emission properties of OLEDs. The most important distinction to be made is between the definitions of external and internal quantum efficiency. For display applications, the commonly accepted definition for the

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external quantum efficiency (η_{ext}) is the *ratio of the number of photons emitted by the OLED* into the viewing direction *to the number of electrons injected*. While the external quantum efficiency could also be defined as the ratio of the total number of photons emitted from the device (in all directions) to the number of electrons injected, this definition is not as useful for display devices and is markedly more difficult to measure accurately than η_{ext}. OLEDs typically emit light into the half plane bounded on one side by the OLED metal contact (generally the cathode). A large fraction of the light can be waveguided by the substrate (typically glass or plastic) and by the organic layers comprising the organic heterostructure, ultimately emerging out of the edge of the substrate.[3,4] Thus, the total amount of light emitted from the device (surface and edges) is markedly higher than the light emitted in the viewing direction, leading to an efficiency based on the total light emitted which can be up to four times larger than η_{ext}.[3]

The *internal quantum efficiency (η_{int})* is *the ratio of the total number of photons generated within the structure to the number of electrons injected.*[5] This implies that internal and external efficiencies differ by the fraction of light coupled out of the structure into the viewing direction (η_c). Hence,

$$\eta_{ext}(\lambda) = \eta_{int}(\lambda)\,\eta_c(\lambda) \tag{1}$$

An ambiguity in calculating η_{int} using Equation 1 arises since a photon emitted within the structure can be re-absorbed,[3] and in some circumstances re-emitted at a longer wavelength by the organic layers of which the organic heterostructure is comprised. Further problems arise since η_c may vary with OLED drive voltage (and hence current), viewing angle, and with the location and width of the emission zone.

A more significant effect is the variation in the responsivity of the photodetector as a function of wavelength. The gener-

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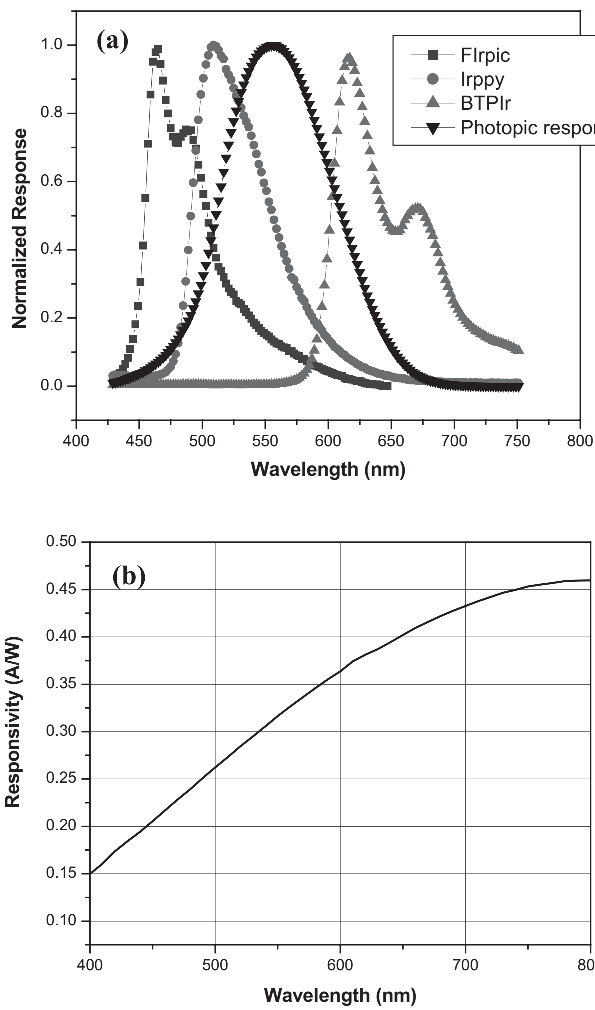

Fig. 1. a) The normalized photopic response of the eye. Note the peak response is 683 lm/W at a wavelength of $\lambda = 555$ nm. Also shown are electrophosphorescence spectra from three different OLEDs employing Ir-based triplet-emitting compounds [18–20]. The variation in detector response across each of these broad asymmetric spectral bands can lead to significant errors in measuring the OLED efficiency if not taken into account as in Equations 2,3 in the text. b) The responsivity, R, as a function of wavelength of a calibrated Si photodiode frequently used in OLED efficiency measurements [8].

ally broad spectral emission of OLEDs can introduce large errors in measurement if this wavelength dependence of the photodetector is not taken into account. Given a wavelength dependence of the incremental photodiode responsivity between wavelengths λ and $\lambda + \mathrm{d}\lambda$, $R(\lambda) = I_{\mathrm{det}}(\lambda)/f(\lambda)P_{\mathrm{OLED}}(\lambda)$, where $I_{\mathrm{det}}(\lambda)$ is the incremental photocurrent generated in the photodetector by the OLED power ($P_{\mathrm{OLED}}(\lambda)$) emitted at center wavelength, λ, and $f(\lambda) < 1$ is the fraction of light emitted to that coupled into the detector, then the external OLED quantum efficiency is:

$$\eta_{\mathrm{ext}} = \frac{q \int \lambda I_{\mathrm{det}}(\lambda)\mathrm{d}\lambda}{hcfI_{\mathrm{OLED}} \int R(\lambda)\mathrm{d}\lambda} \tag{2}$$

Here, we assume that although an OLED may exhibit microcavity effects that result in a strong angular dependence of the emission intensity on wavelength,[6] the best experimental methods employ large aperture light collection optics (see Sec. 2), such that the wavelength dependence of f is small. Also, the OLED current is I_{OLED}, q is the electronic charge, h is Planck's constant, and c is the speed of light in vacuum. Often, the detector sensitivity is quoted in terms of its own external quantum efficiency, η_{det}, which is simply related to the responsivity via $\eta_{\mathrm{det}} = \mathrm{h}\,c\,R(\lambda)/q\lambda$, in which case Equation 2 can be rewritten as:

$$\eta_{\mathrm{ext}} = \frac{\int \lambda I_{\mathrm{det}}(\lambda)\mathrm{d}\lambda}{fI_{\mathrm{OLED}} \int \lambda \eta_{\mathrm{det}}(\lambda)\mathrm{d}\lambda} \tag{3}$$

As defined, the quantum efficiency is simply a ratio, and if multiplied by 100 %, can be stated in terms of a percentage. For "engineering" display applications, η_{ext} is typically quoted independently of the emission wavelength, as in Equations 2 and 3.

As noted above, the luminous efficiency, η_{L}, in candelas per amp [cd/A] is convenient for quantifying the properties of an OLED for display applications. In many respects, η_{L} is equivalent to η_{ext}, with the exception that η_{L} weights all incident photons according to the photopic response of the eye (i.e., while η_{ext} "weighs" all photons equally; if emitted in the invisible spectral regions they would not contribute to η_{L}). In this case, we define:

$$\eta_{\mathrm{L}} = AL/I_{\mathrm{OLED}} \tag{4}$$

where L is the luminance of the OLED (in [cd/m^2], or equivalently, [nits]), and A is the device active area, which is not necessarily equal to the area of light emission.

A frequently used *display* efficiency unit is the luminous power efficiency, or luminosity (η_{p}) [lm/W]. That is, η_{p} is the ratio of luminous power emitted in the forward direction, L_{P} [lm], to the total electrical power required to drive the OLED at a particular voltage, V, viz: $\eta_{\mathrm{p}} = L_{\mathrm{P}}/I_{\mathrm{OLED}}V$. In terms of the spectrally resolved efficiencies discussed in Equations 1–3, we can calculate η_{p} using the photopic response of the eye. Thus:

$$\eta_{\mathrm{P}} = \frac{\phi_0 \int g(\lambda) I_{\mathrm{det}}(\lambda)/R(\lambda)\mathrm{d}\lambda}{fI_{\mathrm{OLED}}V} \tag{5}$$

The normalized photopic response is described by a spectral shape, $g(\lambda)$ (see Fig. 1a), with a peak value of $\phi_0 = 683$ lm/W at $\lambda = 555$ nm where $g(\lambda = 555\ \mathrm{nm}) = 1$.[2,7] Note that the relationship between luminous efficiency and quantum efficiency strongly depends on the *visible* wavelength content of the OLED spectrum. Hence, the total and wavelength-resolved external quantum efficiencies tend to be useful in understanding the fundamental physical mechanisms responsible for light emission within an OLED, while the luminous power efficiency is useful in interpreting the power dissipated by a device when used in a display. Hence, the wavelength-independent, fundamental unit of power efficiency is the *wall plug efficiency* [W/W], i.e., the *ratio of the total optical power emitted* to the *electrical power injected*, viz.: $\eta_{\mathrm{W/W}} = P_{\mathrm{OLED}}/I_{\mathrm{OLED}}V$.

The units of lumens and candelas are related by 1 cd = 1 lm/sr. For a *Lambertian* source emitting into the half plane, for example, 1 lm = π(1 cd). A summary of the definitions discussed in this section used in quantifying display performance is provided in Table 1.

To understand the relative importance that several of the factors discussed above play in accurately determining the OLED efficiency, in Figure 1 we show the photopic response of the eye,[7] a typical Si photodiode responsivity curve,[8] and the broad spectral outputs of three electrophosphorescent OLEDs emitting in the blue, green, and red spectral regions. It is readily apparent that assuming that R is independent of λ for any one of these emission spectra can lead to sizable errors in determining η_{ext}, η_{int}, etc. The strong variation of $\phi(\lambda)$ and $R(\lambda)$ in the red and blue spectral regions tend to introduce the largest measurement errors if not properly considered as above.

With the definitions described here, it should be straightforward to measure these several different efficiencies, thereby fully characterizing a device and its constituent materials. However, as noted above, the often-used assumption that the emission is Lambertian is rarely correct for an OLED due to interference effects compounded by broad emission bandwidths. At one level, deviations from Lambertian behavior do not matter since a display is often viewed normal to its surface which is the preferred direction along which the luminance measurement is made. To understand whether the device characteristics measured genuinely represent an improvement in materials properties or the result of an optical geometry that favors forward directed emission would, however, require careful checks on differences in emission pattern from device to device. It would also be possible to have a geometry that gave rise to a suppression of forward directed emission, and which might therefore result in a material or device structure being erroneously rejected as performing poorly.

To better appreciate how to make measurements that are independent of the details of the OLED emission pattern, we now discuss means for measuring OLED efficiency that, if carefully employed, can provide a basis on which accurate comparisons of results in different laboratories can be made.

2. Efficiency Measurements

If the OLED emission were Lambertian, one could simply measure the device performance using a commercial luminance meter. The luminance meter collects light emitted from a fixed diameter spot on the display surface and into a specified (small) solid angle about the surface normal, and calculates a value of the surface luminance, B, in cd/m^2. The meter uses a calibrated Si photodiode to detect the light, and the conversion of the diode photoresponse into a luminance value is done by the instrument itself, but with the implicit assumptions that the emission pattern is Lambertian and that the meter is *oriented perpendicularly* to the device emitting surface. The recorded luminance value then allows for a calculation of the luminous efficiency η_{L} [cd/A] from knowledge of the driving current density, $J_{\text{OLED}} = I_{\text{OLED}}/A$. Given the voltage at which η_{L} is measured, it is then straightforward to obtain η_{P}. Several researchers have applied this method to infer the physically precise parameter, η_{ext}.[9–11] While simple, this method is vulnerable to incurring large measurement inaccuracies, and hence should be used primarily for characterizing actual *display* performance.

A direct and accurate means for measuring the external quantum efficiency of the OLED employs a calibrated photodetector used in a measurement set-up requiring a minimal amount of correction for losses due to lenses, overfilling of the detector active area with light, conversion between lumens to percent, etc. That is, the optimum measurement geometry has a coupling factor, f, as close to unity as possible (cf., Eqs. 2,3). A particularly accurate and convenient configuration for such a measurement is shown in Figure 2a. The main objective is to detect every photon emitted into the forward direction using a calibrated detector, such that $f \approx 1$, independently from λ. One means to do this is to use a detector whose area is considerably larger than that of the OLED (a condition known as "under filling" of the detector active area), and then placing the OLED very close to the detector without any intervening optics.[12–14] It is also necessary to mask photons emerging from the substrate edges from the detector. One means for doing this is by coating the edges with black paint or wax, or by en-

Table 1. Definitions of efficiencies used in OLED characterization.

Quantity	Symbol	Units	Expression
OLED Efficiencies:			
External Quantum	η_{ext}	–	$\dfrac{q\int\lambda I_{\text{det}}(\lambda)\text{d}\lambda}{\text{hc}fI_{\text{OLED}}\int R(\lambda)\text{d}\lambda} = \dfrac{\int\lambda I_{\text{det}}(\lambda)\text{d}\lambda}{fI_{\text{OLED}}\int\lambda\eta_{\text{det}}(\lambda)\text{d}\lambda}$
Internal Quantum	η_{int}	–	$\eta_{\text{ext}}/\eta_{\text{c}}$
Wall Plug	$\eta_{\text{W/W}}$	–	$P_{\text{OLED}}/I_{\text{OLED}}V$
Luminous Power	η_{P}	lm/W	$L_{\text{P}}/I_{\text{OLED}}V = \dfrac{\phi_0\int g(\lambda)I_{\text{det}}(\lambda)/R(\lambda)\text{d}\lambda}{fI_{\text{OLED}}V}$
Luminance	η_{L}	cd/A	AL/I_{OLED}
Detector Efficiencies:			
Responsivity	R	A/W	$I_{\text{det}}/fP_{\text{OLED}} = I_{\text{det}}/P_{\text{inc}}$
External Quantum	η_{det}	–	$\text{hc}R/q\lambda$

Definition of terms: λ = wavelength; $I_{\text{det}}(\lambda)$ = photocurrent detected for light incident at wavelengths between λ and $\lambda + \text{d}\lambda$; $R(\lambda)$ = incremental detector responsivity wavelengths between λ and $\lambda + \text{d}\lambda$; $P_{\text{inc}}(\lambda)$ = power incident on the detector wavelengths between λ and $\lambda + \text{d}\lambda$; q = electronic charge; h = Planck's constant; c = speed of light in vacuum; f = OLED-to-detector coupling factor (< 1); P_{OLED} = total optical power emitted by the OLED; I_{OLED} = OLED current; ϕ_{o} = peak photopic response of the eye; $g(\lambda)$ = photopic response shape function; V = OLED drive voltage to obtain I_{OLED}; L_{P} = OLED luminous power [lm]; L = OLED luminance [cd/m^2]; A = OLED active area.

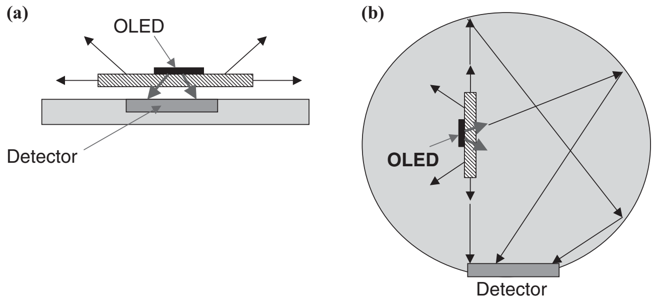

Fig. 2. Preferred experimental geometries for measuring a) the external quantum efficiency, and b) the internal quantum efficiency of an OLED.

suring that the detector is considerably smaller than the OLED substrate.[15] Using this arrangement, the external quantum efficiency of the OLED is simply and directly inferred from the detector photocurrent.

The most common method of approximately measuring *internal* quantum efficiency is to place the OLED into an integrating sphere containing a calibrated detector, and then measuring all photons output from the device[16] (Fig. 2b). Three difficulties arise from this method: i) The response of the photodiode is generally not uniform over the broad spectral output of an OLED (see Fig. 1). As in the case of the external efficiency measurement, the spectral response of the photodiode must be understood and calibrated across the entire OLED emission spectrum to accurately obtain the efficiency from the photocurrent. ii) To obtain η_{int} from the OLED light output, one must understand all sources of internal loss in the structure. Such loss can arise from absorption in the thin films themselves, from the transparent anode, and from surface plasmons, free carrier absorption, and other effects associated with contacts. Due to the uncertainties inherent in calculation of the corresponding correction factors, the internal quantum efficiency can contain significant systematic errors.[3,4] iii) Losses due to shadowing by the probes and other fixtures (e.g., the baffle used to prevent direct irradiation of the detector) within the sphere must also be considered and "backed out" of the measurement.

It is apparent that the internal efficiency will be several times greater than the external efficiency, as the integrating sphere captures nearly all the photons emitted in the device active region and that are subsequently emitted into all directions, not just in the forward viewing direction.[16] Placing the OLED inside the sphere makes it possible to collect all photons emitted, including those that emerge from the edge of the substrate following in-place waveguiding.

Note that this latter process is *not* a measurement of the display-relevant (forward emitted) *external* quantum efficiency; the source of some considerable confusion in the literature. To make a more reasonable measurement of the external quantum efficiency in an integrating sphere requires that the edge-emitted light be prevented from reaching the detector. This can be achieved by thoroughly masking the LED with black paint or wax that absorbs the in-plane waveguided and scattered light.

Once the external efficiency is measured as a function of I_{OLED} and V, and the device emission spectrum is also determined using calibrated detectors, then the luminance, B, luminance efficiency, η_{L}, and luminous power efficiency, η_{p}, can be calculated using standard values for the photopic response of the eye. Unfortunately, doing this process in the "reverse direction" requires that the output emission pattern, meter calibrations, and other geometric factors are well known. Due to deviations from simple Lambertian emission patterns characteristic of most OLEDs,[17] this assumption can lead to significant errors and hence should be avoided.

3. Conclusions

We have provided several formal definitions and described simple but accurate techniques for quantifying the quantum and power efficiencies of OLEDs used in display applications. Note that when any efficiency values are quoted, it is strictly necessary to also specify the values of J_{OLED}, V, and L at which the corresponding measurements were undertaken. This provides all of the information needed to understand the display relevance of any reported efficiency value. A recommended approach is to report the efficiency, J_{OLED} and V at a luminance $L = 100\ \mathrm{cd\,m^{-2}}$, a typical computer screen brightness. A more demanding, but more relevant approach would be to graphically report the variation of the efficiency with J_{OLED}, V, and L. A large efficiency reported at a luminance of only a few candelas per meter squared is of no practical interest, although it may have relevance in understanding fundamental materials or device characteristics. Nevertheless, it is remarkable how many papers quote an impressive efficiency without specifying these three critical parameters, making it impossible to determine whether the efficiency is in fact of any practical interest.

By following the methods described in this paper, measurements made in disparate laboratories testing a wide range of materials and device structures should agree, to within small experimental errors, on the properties of the subject devices.

[1] C. P. Halsted, *Information Display* **1993**, *March*.
[2] W. L. Wolfe, *Introduction to Radiometry: Tutorial Texts in Optical Engineering, v. TT29*, SPIE Optical Engineering Press, Bellingham, WA **1998**.
[3] V. Bulovic, V. B. Khalfin, G. Gu, P. E. Burrows, D. Z. Garbuzov, S. R. Forrest, *Phys. Rev. B* **1998**, *58*, 3730.
[4] J.-S. Kim, P. K. H. Ho, N. C. Greenham, R. H. Friend, *J. Appl. Phys.* **2000**, *88*, 1073.
[5] S. M. Sze, *Physics of Semiconductor Devices*, Wiley, New York **1981**.
[6] N. C. Greenham, R. H. Friend, D. D. C. Bradley, *Adv. Mater.* **1994**, *6*, 251.
[7] A. Ryer, *Light Measurement Handbook*, International Light, Newburyport, MA **1997**.
[8] Si Photodiode 818UV.
[9] H. Y. Chen, W. Y. Lam, J. D. Luo, Y. L. Ho, B. Z. Tang, D. B. Zhu, M. Wong, H. S. Kwok, *Appl. Phys. Lett.* **2002**, *81*, 574.
[10] J. Kido, Y. Iizumi, *Appl. Phys. Lett.* **1998**, *73*, 2721.
[11] T. Tsutsui, M. J. Yang, M. Yahiro, K. Nakamura, T. Watanabe, T. Tsuji, Y. Fukuda, T. Wakimoto, S. Miyaguchi, *Oyo Butsuri* **1999**, *38*, L1502.
[12] P. E. Burrows, Z. Shen, V. Bulovic, D. M. McCarty, S. R. Forrest, J. A. Cronin, M. E. Thompson, *J. Appl. Phys.* **1996**, *79*, 7991.

[13] L. S. Sapochak, F. E. Benincasa, R. S. Schofield, J. L. Baker, K. K. C. Riccio, D. Fogarty, H. Kohlmann, K. F. Ferris, P. E. Burrows, *J. Am. Chem. Soc.* **2002**, *124*, 6119.
[14] V. Adamovich, J. Brooks, A. Tamayo, A. M. Alexander, P. I. Djurovich, B. W. D'Andrade, C. Adachi, S. R. Forrest, M. E. Thompson, *New J. Chem.* **2002**, *26*, 1171.
[15] C. Adachi, M. A. Baldo, M. E. Thompson, S. R. Forrest, *J. Appl. Phys.* **2001**, *90*, 5048.
[16] X. Gong, M. R. Robinson, J. C. Ostrowski, D. Moses, G. C. Bazan, A. J. Heeger, *Adv. Mater.* **2002**, *14*, 581.
[17] S. Tokito, Y. Taga, T. Tsutsui, *Synth. Met.* **1997**, *91*, 49.
[18] S. Lamansky, P. Djurovich, D. Murphy, F. Abdel-Razzaq, H.-E. Lee, C. Adachi, P. E. Burrows, S. R. Forrest, M. E. Thompson, *J. Am. Chem. Soc.* **2001**, *123*, 4304.
[19] M. A. Baldo, S. Lemansky, P. E. Burrows, M. E. Thompson, S. R. Forrest, *Appl. Phys. Lett.* **1999**, *76*, 4.
[20] M. A. Baldo, D. F. O'Brien, Y. You, A. Shoustikov, M. E. Thompson, S. R. Forrest, *Nature* **1998**, *395*, 151.

