Organic light-emitting devices (OLEDs) with various device configurations have been the subject of intensive research due to their applications in display and lighting.1–4 Considering the microcavity effect, OLEDs can be roughly categorized into two types, i.e., weak microcavity OLEDs and strong microcavity OLEDs. Conventional bottom-emitting OLEDs are weak microcavity devices, while OLEDs with distributed Bragg reflectors or two metallic electrodes are considered as strong microcavity devices. Light emission properties, including the internal quantum efficiency (ηint), external quantum efficiency, exciton lifetime, and angular dependence, are distinct in the two types of OLEDs due to the Purcell effect.5–8

Exciton lifetimes of emitters in planar dielectric micro-cavity structures,9 near a partially reflecting surface,10,11 in weak microcavity OLEDs,12,13 and above metallic gratings14 have been investigated either theoretically or experimentally. In this letter, a comprehensive analysis is given on the modifications of the exciton lifetime and internal quantum efficiency (ηint) for organic light-emitting devices (OLEDs). A linear relation is derived between the exciton lifetime and ηint, which is difficult to measure directly. The internal quantum efficiency can thus be estimated easily through the measurement of the exciton lifetime. The exciton lifetimes for OLEDs with weak or strong microcavity are studied experimentally and theoretically. The modification of the exciton lifetime is well explained through the microcavity effect and surface plasmon resonance. An excellent agreement between the experimental and theoretical results is achieved. © 2007 American Institute of Physics. [DOI: 10.1063/1.2819610]

The theoretical analysis of exciton lifetime is based on a classical approach where the emitter is considered as an electric dipole running at a fixed current and with a random orientation.6,15,16 As a consequence of Fermi’s golden rule, the radiative decay rate Γr(λ) at a wavelength λ in an OLED device is modified to

\[ \Gamma_r(\lambda) = F(\lambda) \cdot \Gamma_0(\lambda), \]  

where \( \Gamma_0(\lambda) \) is the radiative decay rate in the infinite medium. Here, \( F(\lambda) \), the so-called Purcell factor, is the normalized total emission power of the dipole in random orientation (normalized by the total power of the dipole in the infinite medium). It should be noted that here, the emission power coupled to the metal electrode is also included in \( F \). We consider such decay channel as radiative decay since this part of emission can potentially be coupled out from the device through, for example, patterning the substrate.17 In addition, we typically assume that the nonradiative decay rate \( \Gamma_{nr} \) does not change by varying the thickness of the hole-transport layer (HTL) or the electron transport layer (ETL) in the device. The initial quantum efficiency \( \eta_0 \), \( \eta_{int} \), and exciton lifetime \( \tau_{OLED} \) in the OLED are given by

\[ \eta_0 = \int_{\lambda_1}^{\lambda_2} \Gamma_0(\lambda) d\lambda \left/ \int_{\lambda_1}^{\lambda_2} \Gamma_0(\lambda) d\lambda + (\lambda_2 - \lambda_1) \Gamma_{nr} \right., \]  

\[ \eta_{int} = \int_{\lambda_1}^{\lambda_2} F(\lambda) \cdot \Gamma_0(\lambda) d\lambda \left/ \int_{\lambda_1}^{\lambda_2} F(\lambda) \cdot \Gamma_0(\lambda) d\lambda + (\lambda_2 - \lambda_1) \Gamma_{nr} \right., \]  

\[ \tau_{OLED} = \frac{\int_{\lambda_1}^{\lambda_2} F(\lambda) \Gamma_0(\lambda) d\lambda}{\eta_0 \int_{\lambda_1}^{\lambda_2} F(\lambda) \Gamma_0(\lambda) d\lambda} \left/ \int_{\lambda_1}^{\lambda_2} \Gamma_0(\lambda) d\lambda + 1 \right. - \eta_0, \]  

where \( (\lambda_1, \lambda_2) \) is the wavelength range of the emission and \( \tau_0 \) corresponds to the average lifetime of the excitons.
is the exciton lifetime of the bulk emitting material. Equation (4) can be written as

$$\tau_{\text{OLED}} = \tau_0(1 - \eta_{\text{int}})/(1 - \eta_t).$$  

(5)

From Eq. (5), one observes that $$\tau_{\text{OLED}}$$ linearly depends on $$\eta_{\text{int}}$$, which means that $$\eta_{\text{int}}$$ can be determined from $$\tau_{\text{OLED}}$$. As shown above, the Purcell factor $$F(\lambda)$$ is a crucial quantity, which can be evaluated with the knowledge of the electric field at the location of the dipole. The electric field can be efficiently calculated by integrating the plane wave component of the field along a proper integration path.

In the experiment, europium (Eu) organometallic complexes were used in the OLEDs as the emitters. As shown in Fig. 1, four sets of OLEDs, i.e., devices A, B, C, and D, were fabricated to study the exciton lifetime of Eu ion based emitters in weak microcavity OLEDs (devices A and C) and strong microcavity OLEDs (devices B and D). The Eu complexes of Eu(α-thienyltrifluoracetone)$_2$ (triarylphosphine oxide)$_2$ Eu(TTA)$_3$(TPPO)$_2$ and Eu(dibenzoylmethanato)$_2$(bathophenanthroline) Eu(DBM)$_3$, bath were used as the emitting layer in devices A and B and devices C and D, respectively. The widely used material of bis(3-methylphenyl)-diphenyl-benzidine was used as the HTL. UV emissive (1,3,5-benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) was used as the ETL. All the materials were evaporated by thermal vacuum deposition at a pressure of 10$^{-6}$ Torr. The thickness of each layer is indicated in the figure, where $$x$$ denotes a variable thickness and $$t$$ is the total thickness of the organic layers. The transient photoluminescence (PL) was excited by pulse laser at 337 nm.

Figure 2 shows the measured transient PL intensities of the two devices, i.e., devices A and B with the same total thickness of organic layers of 115 nm. The inset shows the Purcell factors of the two devices and the intrinsic spectrum of Eu complexes.

![Image](70x62 to 277x192)

**FIG. 1.** Schematic diagrams of the devices A, B, C, and D.

![Image](338x608 to 537x739)

**FIG. 2.** The measured transient PL intensity of devices A (open circles) and B (open triangles) with the total thickness of organic layers of 115 nm. The inset shows the Purcell factors of the two devices and the intrinsic spectrum of Eu complexes.

![Image](215x86 to 296x109)

**FIG. 3.** Internal quantum efficiency $$\eta_{\text{int}}$$ varies as a function of the normalized exciton lifetime ($$\tau_{\text{OLED}}/\tau_0$$) for various $$\eta_0$$.
which indeed corresponds to the dip of the solid line at $t = 140$ nm in Fig. 4(a).

Figure 4(b) shows the experimental (symbols) and theoretical (lines) exciton lifetimes of devices C and D as functions of $t$. Here, $\tau_0$ is recalibrated to be 0.33 ms for Eu(DBM)$_3$bath. Again, we observe a good agreement between the experimental and theoretical results. One sees that the exciton lifetimes of all the devices drop significantly as the distance from the LiF–Al cathode becomes short. This is due to the excitation of the surface plasmon mode along the LiF–Al cathode which exists in both types of OLEDs. Meanwhile, the microcavity effect is also pronounced for devices C and D and, thus, the exciton lifetimes of device D are shorter. For device D, the simulated and experimental results agree well in trend but have small discrepancy in absolute values. This may be due to some deviation in measuring the thickness of the silver film.

In conclusion, a comprehensive analysis has been given on the modifications of the exciton lifetime ($\tau_{\text{LED}}$) and internal quantum efficiency ($\eta_{\text{in}}$) in OLEDs. We have shown that $\tau_{\text{LED}}$ has a linear relation with $\eta_{\text{in}}$. This means that $\eta_{\text{in}}$, which is important but difficult for a direct measurement, can be estimated easily by measuring $\tau_{\text{LED}}$. The modifications of exciton lifetimes in various OLEDs have been well explained through the microcavity effect and surface plasmon effect.

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5. E. M. Purcell, Phys. Rev. 69, 681 (1946).