Coupling Efficiency Enhancement in Organic Light-Emitting Devices Using Microlens Array—Theory and Experiment

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***Abstract*—Microlens arrays are introduced on glass substrates to improve the out-coupling efficiency of organic light-emitting devices (OLEDs). The microlenses suppress waveguiding loss in the substrate. A theoretical model, based on electromagnetic wave propagation and geometric ray tracing, is developed to simulate the enhancement effects and optimize the structure parameters of the lens pattern. A simple soft-lithography approach is employed to fabricate the microlens array on glass substrates. With the use of an optimized lens pattern, an increase of over 85% in the coupling efficiency of the OLED is expected theoretically. An increase of 70% in the coupling efficiency is achieved experimentally, without detrimental effect to the electrical performance of the OLED.**

***Index Terms*—Coupling efficiency, microlens array, organic light-emitting diodes (OLEDs), soft lithography.**

I. Introduction

HIGH efficiency organic light-emitting diodes (OLEDs) are required for display and solid-state lighting applications. The external quantum efficiency of an OLED is determined by the product of the internal quantum efficiency and light out-coupling efficiency. Devices with nearly 100% internal quantum efficiency have been achieved by using phosphorescent emitting materials [1], [2]. However, the typical out-coupling efficiency is limited by total internal reflection (TIR) to be $\sim$20% [3]. This low coupling efficiency becomes one of the main limitations on overall device performance.

Various methods have been proposed to increase the coupling efficiency. They can be classified into four general schemes: 1) application of corrugated microstructure or two-dimensional photonic crystal structure to increase the coupling efficiency through Bragg-scattering the light bounded in lateral guided modes [4], [5]; 2) modification of the substrate surface to reduce the TIR loss at the substrate–air interface, such as the incorporation of monolayer of silica microsphere in the substrate [6], shaping of the device into a mesa structure [7], patterning polymer microlens array or macro lenses on the substrate [8]–[10], attachment of a diffusive layer on the substrate [11]; 3) insertion of a low index medium between the indium–tin–oxide (ITO) layer and supporting substrates [12]; and 4) using a microcavity structure [13].

Among these techniques, the fabrication of microlens array is simple, and can be easily applied to large area substrates [8]. This method also has the merits that the microlens array is external to the OLED device and, therefore, does not affect its operation. In particular, there is no spectral variation with viewing angle nor any change on device electrical properties. Such a microlens array has also been used on GaN light-emitting diodes (LEDs) to improve the light extraction efficiency [14].

In order to optimize the coupling enhancement factor it is important to study the details concerning the impact of geometrical structure of the microlens. However, little study has been undertaken on analysis of the involved basic physical process and optimization of microlens pattern [8], [9], [14]. In this paper, we develop a theoretical model to quantitatively analyze the performance of the microlens array with various geometrical shapes for the coupling efficiency enhancement of planar OLEDs. In this model, we first investigate the intrinsic weak microcavity effects by a classical electrodynamics method and then search the optimized microlens structure by a geometric ray tracing method. Using these results, microlens arrays with different shapes were fabricated using a simple fabrication process on the glass substrates. An enhancement factor of 1.85 is expected according to simulations and an experimental result of 1.7 has been obtained.

II. Simulation and Optimization

The total out-coupling efficiency (η_{coupl}) of the OLED device can be decomposed into two terms, i.e.,

$$\eta_{\text{coupl}} = \eta_{o-s} \times \eta_{s-a} \quad (1)$$

where η_{o-s} is the fraction of the light from emitting layer into substrate, and η_{s-a} the fraction of light from substrate into air. The latter term is the primary focus in this paper. It has been reported that weak microcavity effects due to highly reflective metallic cathode can lead to substantial changes of η_{o-s} and alter the internal angular distribution $G(\theta)$ of light going into the substrate [15]. Therefore, the intrinsic microcavity effects are first investigated for the characterization of $G(\theta)$. After obtaining the radiation profile inside the glass substrate, we employ the ray tracing method to calculate η_{s-a} [16], [17]. Notice that since the size of the Microlens studied here is much larger than the emission wavelength, refractive rather than diffractive scattering effect is expected to be dominant. The ray tracing

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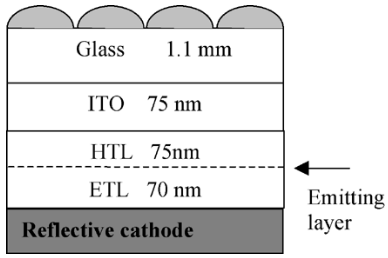

Fig. 1. Schematic structure of an OLED used in this study.

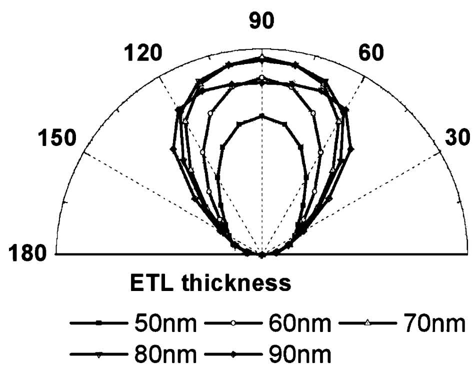

Fig. 2. Light emission angular profile in the glass substrate for different values of the dipole distance from the metallic cathode.

method is very powerful yet simple in analyzing such optical problems.

The total emission is treated as a summation of radiation by randomly alignment incoherent dipole sources. The radiation profiles of the oscillating dipoles are studied using a rigorous classical electrodynamic method based on the Green's function and a plane wave propagation method [18], [19]. Fig. 1 shows the schematic structure of an OLED used in this study. The dipoles are assumed to be randomly aligned in the emitting layer. The device emission characteristics can be obtained by calculating the intensity distribution of the electromagnetic field generated from oscillating dipoles embedded in a planar stratified media. In this calculation, both the dispersion of the materials' optical properties and wide spectrum of the emitting source are taken into account without approximation.

Fig. 2 shows the angular distributions of the light emission in the glass substrate for different values of the dipole distance (d) from the metallic cathode. The dependence of the angular distribution on d is due to the familiar interference effect. It is similar to the dependence of the output on the layer thickness. After spatially integrating the radiation power, it is found that the highest power is achieved at $d = 80$ nm. This value is consistent with the condition for constructive interference which happens when the emitting source is at a quarter wavelength, $\lambda/4n$, from metallic reflector. For the Alq_3 emitter, λ is 520 nm and the refractive index n is 1.69. We notice that the profile for d of 70 nm is close to that for d of 80 nm. Consideration for lower electrical driving voltage is required for thinner organic thickness, the optimized d is confirmed to be about 70 nm.

Based on the optimized radiation profile inside glass substrate, we first calculate the extraction efficiency of light from substrate to air, η_{s-a}, for the conventional planar surface device, which can be expressed as

$$\eta_{s-a} = \frac{\int_0^{90^0} G(\theta) \cdot \sin\theta \cdot T(\theta) d\theta}{\int_0^{90^0} G(\theta) \cdot \sin\theta \cdot d\theta} \tag{2}$$

where T is the transmission coefficient at the interface. It can be calculated using the Fresnel equations. $T(\theta)$ becomes zero at angles larger than the critical angle at glass–air interface. In (2), we assume that any light incident at angles less than critical angle and internally reflected by the substrate-air interface is completely lost due to a completely absorbing cathode. The fraction of η_{s-a} is calculated to be 0.47, which means that nearly half of the light could be extracted from the surface side of the glass substrate. Therefore, the highest enhancement factor that can be achieved by recovering the TIR loss at the substrate/air interface is about 2.1.

The optimized microlens structure can then be searched by a ray tracing method. In the ray tracing method, the energy of the light in the substrate is regarded as being transported along certain rays while the intensity of each ray is distributed according to the radiation profile obtained analytically above. These rays are refracted and reflected at the substrate–air interface. Interface modification by the microlens array changes both the path and intensity of the refracted light into air based on the law of refraction. The calculation takes into account the rays which are bounced back and forth between the cathode and substrate–air interface and have a chance to escape out. The rays escaping from the substrate surface are spatially integrated to determine the total output energy. We then calculate the coupling efficiency enhancement factor by comparing the output energy of the devices with and without the microlens array. The calculation has considered the reflection at the interfaces of microlens–air and glass–microlens interfaces for all devices. To obtain a high accuracy, the number of the rays is set to be over ten million, which makes the calculation nontrivial.

In the calculation, the glass substrate has a size of 2.5×2.5 cm^2 with the thickness of 1 mm and the emitting dipole is located at the center. The microlens is assumed to have the same refractive index $(n = 1.48)$ as that of the glass substrate. The enhancement effect produced by microlens array is determined by two factors: the diameter (D) and the height (H) of the lens. The focal length of the lenslet is determined by D and H through the lensmaker's formula. In principle, the lenses should overlap to eliminate any open area. In practice, there is always a gap between the lenses due to the reflow process. In this calculation, the spacing between lenses is fixed to be 1 μm because this is the resolution that can be easily obtained by conventional microfabrication technology. Fig. 3 illustrates the calculated coupling enhancement factor as a function of the lens height for various lens diameters. The enhancement factor increases with the lens height, regardless of the lens diameter, then decreases after reaching the highest value. The highest value is obtained when the lens has is a hemisphere structure. As depicted in Fig. 3, the coupling efficiency can be enhanced by up to 85% for an optimized microlens pattern. This value is slight less than the theoretical limitation. The discrepancy is primarily attributed to the nonunity filling factor and reflection loss at the lens-air interface.

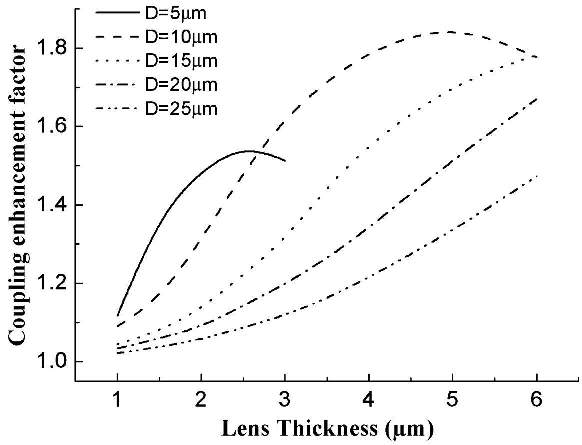

Fig. 3. Out-coupling efficiency enhancement factor as function of the lens height for different lens diameters.

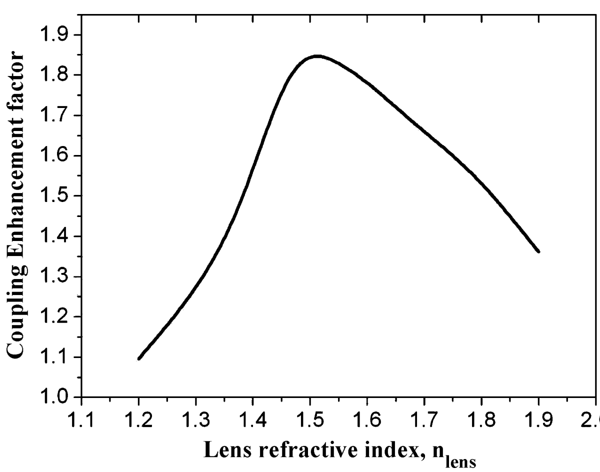

Fig. 4. Out-coupling efficiency enhancement factor as function of the lens refractive index. The lenses have a diameter of 10 μm and a hemispherical structure.

The refractive index of the microlens, n_{lens}, is also one of the important parameters for the coupling efficiencies. Fig. 4 shows the calculated coupling enhancement factor as a function of n_{lens} The lenses in the calculation have an optimized hemisphere structure according to the calculation above and a diameter of 10 μm. With increasing n_{lens} the coupling efficiency increases first, then decreases after reaching the optimal value at $n_{\text{lens}} = 1.5$. This result infers the optimized refractive index of the microlens should match that of the substrate. A lower index leads to TIR loss at the substrate–lens interface. A higher index induces more reflection loss at the substrate–lens and lens–air interface. For the conventional sodium-lime glass substrate, the index of about 1.5 is the optimized value for the microlens.

III. Experiment

The microlens arrays were fabricated using a soft lithographic approach, as shown schematically in Fig. 5(d). First, a layer of photoresist was spin-coated on a glass substrate. Periodic disk "islands" with a diameter of 5, 10, 15, and 20 μm, and a spacing of 1 μm were then formed by conventional photolithography. The photoresist disks were changed to a spherical shape by melting and reflow to form the microlens array. The negative pattern of the photoresist was then transferred to a thermally curable elastomer, poly-dimethyl-siloxane (PDMS), to fabricate the microlens array mold. This PDMS mold was filled with optical epoxy and then adhered to an ITO glass substrate. Using UV light exposure, the epoxy was cured to become a transparent hard film. Finally, the PDMS mold was removed, leaving a thin layer of epoxy microlens array on the glass surface. Fig. 5(a)–(c) show scanning electron micrography (SEM) images of the ordered array of epoxy microlens on ITO glass substrate. It is clear that the lenses have a highly spherical curvature.

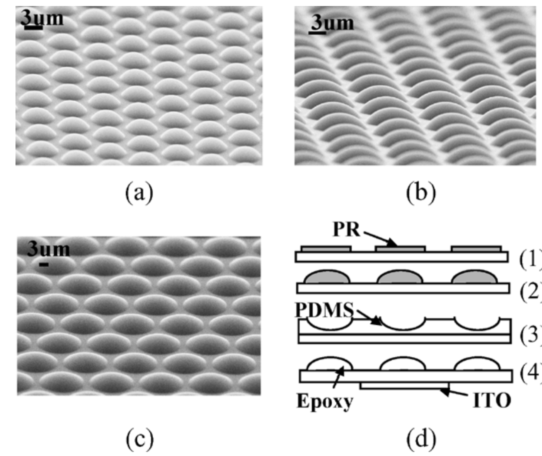

Fig. 5. SEM images of the microlens arrays with diameter of: (a) 5 μm; (b) 10 μm; (c) 15 μm. The spacing between the lenses is 1 μm for all cases. (d) Schematic of the lens fabrication process.

To study the effects of the microlens array on OLED efficiency, we fabricated OLEDs on the glass substrates with microlens array formed on the opposite side. The ITO line was patterned by lithography before microlens fabrication. The OLEDs were made by conventional evaporation with structure of ITO (75 nm)/CuPc (20 nm)/TPD (55 nm)/Alq_3 (70 nm)/LiF (1 nm)/Al (100 nm) A reference device was also fabricated on the ITO glass substrate without the microlens. Devices with 5-, 10-, 15-, and 20-μm diameter microlens arrays are referred to as D5, D10, D15, and D20, respectively.

IV. Results and Discussions

The current density (J), voltage (V), and luminance (L) characteristics of the microlens devices are compared with that of the reference in Fig. 6. The JV curves are identical within measurement uncertainties. This indicates the microlens fabrication process have no effects on the electrical properties of the OLED. At 50 mA/cm^2 the luminance is 1342 cd/m^2, 1783 cd/m^2, 1860 cd/m^2, 1705 cd/m^2, and 1568 cd/m^2 for the reference device, D5, D10, D15, and D20, respectively, which indicates 40% enhancement of the luminance efficiency in the normal direction for the device using 10-μm diameter microlens array. The identity of the JV curves shows evidence that the enhancement in luminance comes from the higher out-coupling efficiency.

To measure the coupling efficiency enhancement, we employ the integrating sphere to obtain the total flux of the light emitted from device front side. The device was attached to the 0.5 inch

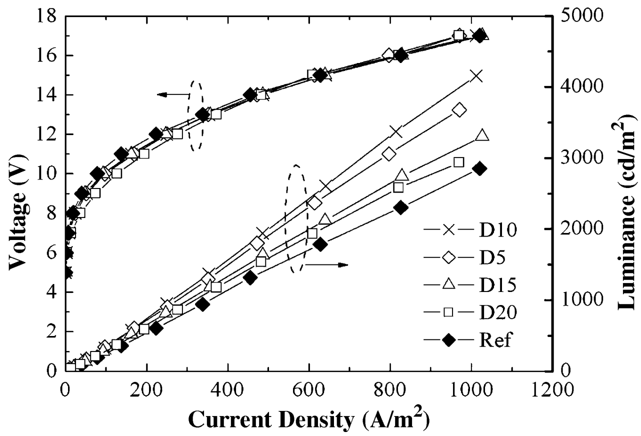

Fig. 6. *L-J-V* curves of the OLED devices with different microlens array pattern and the reference standard. The luminance intensity is measured in the normal direction to the device substrate.

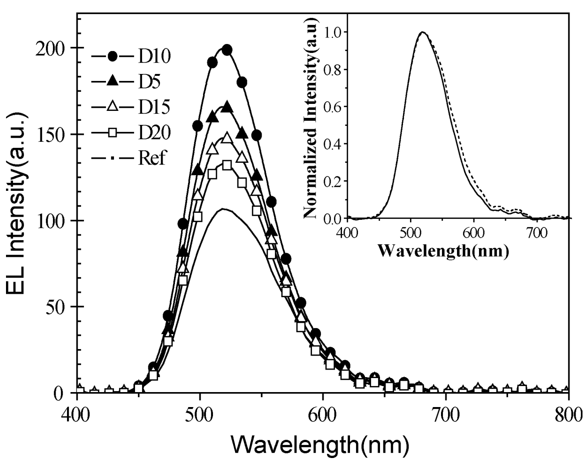

Fig. 7. Emission spectra indicating enhanced light extraction with negligible color shift; inset: normalized EL spectra of D10 under viewing angle of 0° (solid) and 60° (dash).

detector port of a 2-in diameter sphere (IS-020, Labsphere Inc.), which was connected to a spectrometer (PC2000, Ocean Optics Inc.) with an optical fiber. Because the substrate size is larger than the detector port, the edge emission due to the guided light in substrate can be prevented from being collected. Fig. 7 shows the electroluminescence (EL) of various devices under an injection current density of 50 mA/cm^2. The absolute EL can be extrapolated as a product of the measured spectra with a constant determined related to the geometry of the integrating sphere. Thus the coupling efficiency enhancement can be extracted by directly comparing the EL intensities. The total enhancement factor is found to be 1.7, 1.4, 1.3, and 1.2 for devices D10, D5, D15, and D20, respectively, after integration of the EL spectra. These factors are higher than those obtained for the normal direction, because the light intensity more efficiently enhanced at larger viewing angles for the devices with microlens array [8]. The inset of Fig. 7 shows the spectra of OLED with microlens at 0° and 60° from the substrate normal direction. There is no change of color with the viewing angle because the microlenses are much larger than the emission wavelength. Only refractive effects are dominant rather than interference and other undesirable diffractive effects.

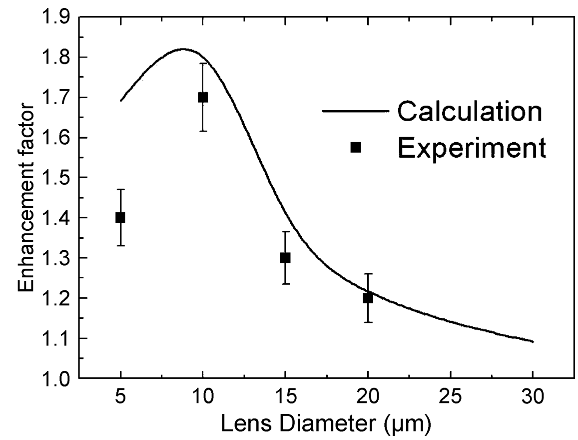

Fig. 8. Simulated (solid line) and measured out-coupling efficiency enhancement factors as a function of microlens diameter.

Assuming that the lens has a perfect spherical structure and there is no shrinkage during the lens fabrication, we can obtain the microlens height according to simple geometry as [20]:

$$t = \frac{H}{6}\left(3 + 4\frac{H^2}{D^2}\right) \tag{3}$$

where t is the thickness of the photoresist before melting. The calculated lens heights are 3.5, 4.3, 5.15, and 5.45 μm for D5, D10, D15, and D20, respectively. Fig. 8 compares the calculated and measured enhancement factors as a function of the lens diameter. As expected, D10 has the highest enhancement factor because its lens surface is nearly hemispherical. The experimental enhancement factors are generally smaller than the simulated ones. We believe the discrepancy is caused by absorption loss of the light in the layered media and deviations from ideal spherical lens shape. However, one can see that the variation trend of the experiment results agree well with the simulated results, confirming our model can predict the optimized lens pattern effectively.

V. Conclusions

In conclusion, we have demonstrated that a microlens array can enhance the coupling efficiency of OLED by reducing waveguiding in the glass substrate. The dependence of the enhancement factor on the microlens structure was investigated by a theoretical model based on ray tracing method. In our calculation, the enhancement of light extraction of up to 85% was predicted from an optimized lens pattern with a hemispherical structure. Experimentally, a high enhancement factor of 1.7 was obtained. There was no change to the other electrical performance of the OLED. This coupling efficiency enhancement method can be combined with high internal quantum efficiency electrophosphorescent OLEDs to fabricate super-high efficiency devices. The proposed model can also be applied to other coupling enhancing technology involving substrate air interface modification.

Finally, it should also be pointed out that the microlens array also induces blurring of the image due to the finite size of the lenses. For high resolution displays, this may not be desirable. We believe that the microlens array is best used in OLED for lighting applications.

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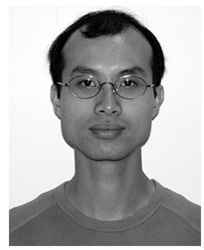

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