# Improvement of output coupling efficiency of organic light-emitting diodes by backside substrate modification

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The emission intensity of an organic light-emitting diode at normal viewing angle and the total external emission efficiency have been increased by factors of 9.6 and 3.0, respectively, by applying spherically shaped patterns to the back of the device substrate. The technique captures light previously lost to waveguiding in the substrate and, with proper choice of substrate, light previously lost to waveguiding in the organic/anode layers. A method of applying the technique using laminated films and an optical model for evaluating coupling efficiency are also presented. © *2000 American Institute of Physics.* [S0003-6951(00)01613-2]

A critical factor in determining the power efficiency of organic light emitting diodes (OLEDs) is the coupling efficiency ($\eta_{\mathrm{cp,ext}}$) with which internally generated light is coupled out of the device. In this article we demonstrate a method based on surface texturing of the substrate which, when compared with devices fabricated on typical planar glass substrates, can at least double the coupling efficiency when glass substrates are used and at least triple it when high-index plastic substrates are used. The work is accompanied by modeling, as well as demonstration of how the far field intensity distribution can be tuned.

The typical OLED consists of a multilayer sandwich of a planar glass substrate ($t_{\mathrm{sub}}\sim 1$ mm, $n_{\mathrm{sub}}=1.51$), a layer of indium–tin–oxide (ITO) ($t_{\mathrm{ITO}}\sim 100$ nm, $n_{\mathrm{ITO}}\sim 1.8$), one or more organic layers ($t_{\mathrm{org}}\sim 0.1$ nm, $n_{\mathrm{org}}=1.6$–$1.8$), and a reflecting cathode (e.g., Mg:Al or Li:Al), where $t$ refers to the layer thickness and $n$ refers to the index of refraction. The coupling efficiency problem in OLEDs is well known and results from light trapping in the high-index materials.[1] This problem can be easily analyzed if microcavity effects are ignored and there is no diffuse scattering at interfaces. If all surfaces are planar, light emitted from the backside of the substrate will originate only from light emitted at angles less than the organic-air critical angle, $\theta_{\mathrm{org},c1}$, given by $\sin^{-1}(n_{\mathrm{air}}/n_{\mathrm{org}})$ (ray I in Fig. 1). Light emitted at angles larger than $\theta_{\mathrm{org},c1}$, but smaller than the organic-substrate critical angle, $\theta_{org,c2}$, given by $\sin^{-1}(n_{\mathrm{subs}}/n_{\mathrm{org}})$, are trapped in the substrate (ray II in Fig. 1). Light emitted at angles larger than $\theta_{\mathrm{org},c2}$ are trapped in the organic and ITO layers collectively (ray III in Fig. 1), and will likely be quickly absorbed by the ITO or at the cathode.[2]

Assuming the cathode is a perfect reflector, so that light internally reflected towards the cathode and light reflected from the glass–air interface near the critical angle is eventually emitted, and assuming isotropic emission in the organic layer, it is well known that the fraction of generated light escaping from the substrate, $\eta_{\mathrm{cp,ext,pl}}$ is[3,4]

$$\eta_{\mathrm{cp,ext,pl}}=\int_0^{\theta_{\mathrm{on},c1}}\sin\theta d\theta=1-\cos\theta_{\mathrm{org},c1}\approx\frac{1}{2n_{\mathrm{org}}^2},\qquad(1)$$

where the subscript pl denotes the case of a planar substrate. The fraction of light trapped in the substrate, $\eta_{\mathrm{cp,subs,pl}}$ and in the organic/ITO layers, $\eta_{\mathrm{cp,org}}$, are given by

$$\eta_{\mathrm{cp,subs,pl}}=\cos\theta_{\mathrm{org},c1}-\cos\theta_{\mathrm{org},c2},\qquad(2)$$

$$\eta_{\mathrm{cp,org}}=\cos\theta_{\mathrm{org},c2}.\qquad(3)$$

Furthermore, the external luminous intensity distribution, where $\theta_{\mathrm{ff}}$ is the viewing angle in the far field, under the same assumptions, is given by[5]

$$I_{\mathrm{ext,pl}}(\theta_{\mathrm{ff}})=\frac{F}{2\pi}\frac{n_{\mathrm{air}}^2\cos\theta_{\mathrm{ff}}}{n_{\mathrm{org}}^2\sqrt{1-\left(\frac{n_{\mathrm{air}}}{n_{\mathrm{org}}}\sin\theta_{\mathrm{ff}}\right)^2}},\qquad(4)$$

which approximately resembles the cosine intensity profile of a Lambertian emitter. In Eq. (4), we assume that all light incident an interface at angles less than the critical angle is completely transmitted (referred to as the $T=1$ case); one can also calculate $I_{\mathrm{ext,pl}}(\theta_{\mathrm{ff}})$ assuming the other extreme, where any light incident at angles less than the critical angle and internally reflected by the substrate–air interface is completely lost due to a completely absorbing cathode. This was calculated in Fig. 2(a) (labeled $T\neq 1$) using the standard Fresnel equations (omitted for brevity) for the substrate–air interface assuming equal contributions from transverse electric and transverse magnetic modes. Both produce similar profiles at small angles, and differ slightly at large angles [see Fig. 2(a)].

For glass substrates and typical index of refraction organic layers (e.g., $n_{\mathrm{org}}\sim 1.7$), the external coupling efficiency is only $\sim$17%. Most internally generated light is thus trapped

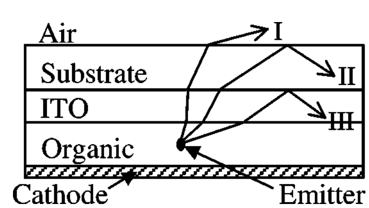


FIG. 1. Ray diagrams in planar OLEDs demonstrating loss by light trapping in the substrate (ray II) and in the organic/anode layers (ray III). Only light emitted at sufficiently small angles will escape (ray I).

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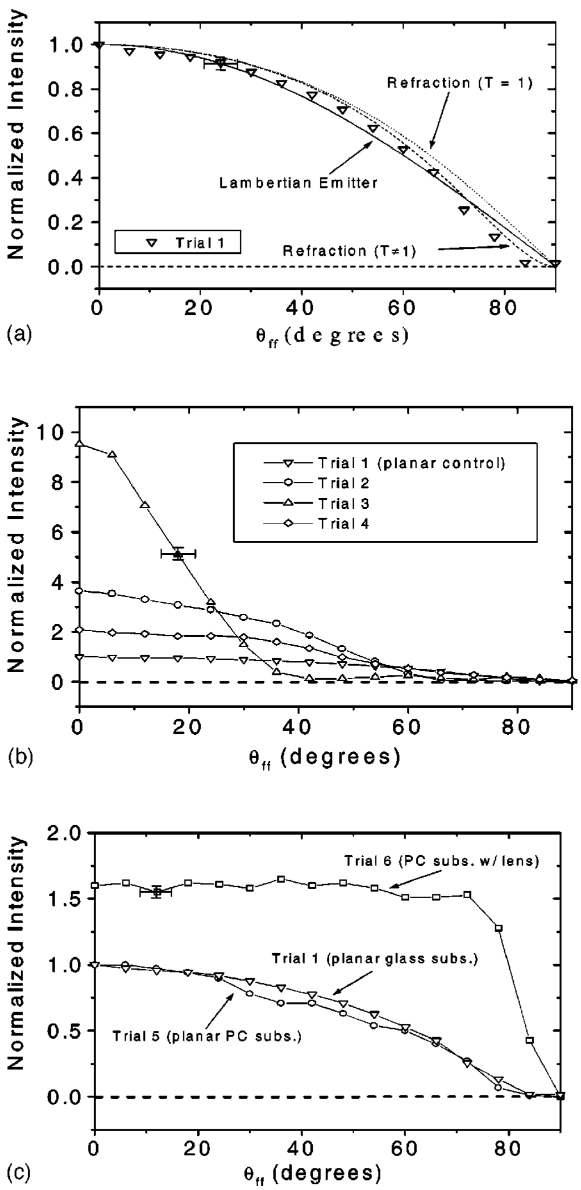


FIG. 2. (a) Measured far-field intensity distribution pattern for planar glass substrate and the expected profiles of a Lambertian emitter, and the $T=1$ [Eq. (4)] and $T\neq 1$ refraction models. (b) Experimental results for glass substrate devices with and without lenses. (c) Experimental results for PC substrate devices with and without lenses. along with the planar glass substrate results.

within the device. The external coupling efficiency has been improved by a factor of $1.9\pm 0.2$ by etching grooves in the glass around the OLED to redirect light trapped in the substrate and organic/ITO layers.[5] This method does not lend itself well to the fabrication of device arrays, however, where metal lines and/or circuitry for passive or active matrix drivers would have to cross the deep grooves.

A solution to the light-trapping problem which preserves a planar surface for device processing is to pattern the backside of the substrate in the shape of a sphere with the emitting layer at its center, Fig. 3(a). For spherical shapes subtending a large solid angle of emitted rays, light previously trapped in the substrate would be emitted. Not only would the total external efficiency be increased, but because all rays would impinge normally on the substrate–air interface, the normal emitted intensity would also be increased as a result of the reduced refraction. The far-field intensity distribution

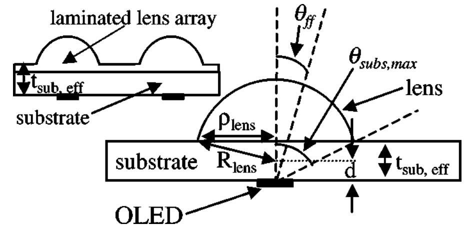


FIG. 3. Use of spherical surface features to improve external efficiency. The relevant parameters shown are given for each experimental trial in Table I. Note that the ray used to define the far-field angle, $\theta_{\mathrm{ff}}$, is drawn for the $d=0$ case, while in the diagram $d$, the offset between the center of curvature of the lens and the OLED, is drawn as nonzero so that it can be clearly identified. Inset: Spherical features implemented as a plastic lens array laminated to a planar substrate.

$[I_{\mathrm{ext,sp}}(\theta_{\mathrm{ff}})]$ would then take on the same form as inside the substrate $[I_{\mathrm{subs}}(\theta_{\mathrm{subs}})]$,

$$I_{\mathrm{ext,sp}}(\theta=\theta_{\mathrm{ff}})=I_{\mathrm{subs}}(\theta=\theta_{\mathrm{subs}})$$

$$=\frac{F}{2\pi}\frac{n_{\mathrm{subs}}^2\cos\theta}{n_{\mathrm{org}}^2\sqrt{1-\left(\frac{n_{\mathrm{subs}}}{n_{\mathrm{org}}}\sin\theta\right)^2}}, \qquad (5)$$

where the subscript sp denotes the case of the spherical substrate features. This concept has long been known for crystalline semiconductor LEDs[6,7] and spherical substrate features have previously been used with OLEDs to eliminate microcavity effects, but the effect on external coupling efficiency and the far field emission pattern was not described.[2] As will be shown, by matching the index of the substrate to the index of the emitting material in addition to shaping the substrate, one can potentially eliminate all of the external coupling losses in the device.

Increased efficiencies were demonstrated by fabricating OLEDs on glass and polycarbonate (PC) substrates coated with ~100 nm of ITO. The OLEDs were made by spinning on a single poly-(*N*-vinycarbazole)(PVK)/2-(4-biphenyl)-5-(4-tert-butylphenyl)-1,3,4-oxadiazole(PBD)/Coumarin 6 (C6) layer, and evaporating a Mg:Ag cathode.[8] The index of refraction of the organic layer was measured to be 1.67 $\pm 0.01$ by ellipsometry at $\lambda=634$ and $\lambda=830$ nm. The typical device cathode was a circle 1.75 mm in diameter.

Figure 2(a) shows the far field pattern of a planar device on a glass substrate (see trial 1 in Table I), along with the expected profile of a Lambertian emitter, and the $T=1$ [Eq. (4)] and $T\neq 1$ refraction models. Within our uncertainty, each profile reasonably matches the data. In a first experiment (trial 2), a glass planoconvex lens was attached using an index matching gel to the substrate under an OLED fabricated on planar glass. [Measured far-field patterns for trials 1–4, as given in Figs. 2(a) and 2(b), were normalized by the normal emitted intensity of the planar device (trial 1)]. A clear increase in the normal emission (3.6×) and the total integrated emission (2.0×) (not including edge emission) occurred. Note that the far-field intensity, $I_{\mathrm{ff}}(\theta_{\mathrm{ff}})$, must be weighted by $\sin(\theta_{\mathrm{ff}})$ when integrating over $\theta_{\mathrm{ff}}$ to get the total emission intensity (due to the larger solid angle at larger $\theta_{\mathrm{ff}}$). When the lens was added, light emitted out of the edge of the glass (i.e., light trapped in the substrate) was reduced by $42\%\pm 6\%$, clearly demonstrating redirection of light previ-

TABLE I. Substrate and lens parameters [as defined in Fig. 2(a)] for different external coupling experiments. $I_{normal}/I_0$ and $F/F_0$ represent the ratio of normal emission intensity and total surface emitted light respectively to the results obtained for identical devices fabricated on planar substrates of the same substrate material.

| Trial | Substrate material | Lens material | $R_{lens}$ (mm) | $\rho_{lens}$ (mm) | $t_{subs,eff}$ (mm) | $\theta_{subs,max}$ | $d$ (mm) | $I_{normal}/I_0$ $\pm 0.1$ | $F/F_0$ $\pm 0.1$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Glass ($n=1.51$) | N/A | N/A | N/A | 0.7 | N/A | N/A | 1.0 | 1.0 |
| 2 | Glass ($n=1.51$) | Glass ($n=1.51$) | 3.4 | 3.4 | 0.7 | 78° | +1.0 | 3.6 | 2.0 |
| 3 | Glass ($n=1.51$) | Glass ($n=1.51$) | 3.4 | 3.4 | 2.0 | 60° | +2.3 | 9.5 | 1.6 |
| 4 | Glass ($n=1.51$) | Silicone ($n=1.41$) | 2.7 | 2.4 | 1.9 | 51° | +0.6 | 2.1 | 1.6 |
| 5 | PC ($n=1.59$) | N/A | N/A | N/A | 1.0 | N/A | N/A | 1.0 | 1.0 |
| 6 | PC ($n=1.59$) | Epoxy ($n=1.61$) | 2.7 | 2.4 | 1.0 | 67° | −0.3 | 1.6 | 3.0 |

ously lost to waveguiding in the substrate into the forward direction. Removing the lens and the index matching gel caused the emitted the light profile to revert back to its original shape.

The sharp peaking of the emission profile (i.e., the increase in the normal emission and the decrease in large-angle emission) occurred because the OLED was slightly below the center of curvature (but still well above the focal point) of the lens, leading to a slight focusing effect. This effect was exaggerated in trial 3, when the substrate thickness was intentionally increased from 0.7 to 2.0 mm. This resulted in an even more highly focused beam, with a nearly 10× increase in normal emitted intensity.

To demonstrate a practical method for implementing this technique in manufacture, we then created a thin array of transparent microlenses in a molded silicone sheet ($n=1.41$). Liquid General Electric RTV615 silicone rubber compound was poured after mixing into a machined teflon mold and allowed to harden, with resulting lens dimensions given in Table I for trial 4. This sheet was then laminated to the planar glass substrate after OLED fabrication [Fig. 3(b)]. In this case the center of curvature was closer to the OLED, resulting in a less focused emission profile, with decreased normal emission compared to trial 2, but larger large-angle emission. The improvement in total emitted light, however, was limited by the relatively small size of the lens we fabricated.

The above experiments can at best hope to capture light waveguided in the substrate, but not the 43% [calculated from Eq. (3)] of generated light waveguided in the organic ITO layers. To capture this light, high index of refraction substrates must be used. Therefore, devices were made on polycarbonate (PC) substrates ($n=1.59$) to reduce the light waveguided in the organic/ITO layers. A planar device had a far-field pattern similar to that for a glass substrate, as expected from Eq. (3), which has no dependence on the substrate index [Fig. 2(c)]. A lens made from molded epoxy ($n=1.61$) (using the same technique and mold as for the silicone lens) was then applied to the PC substrate. The total emitted intensity was increased by a factor of three. (The data for both the glass and PC substrate planar devices were normalized to their values at 0°, and the data for the epoxy lens on a PC substrate was normalized to the planar PC substrate device at 0°.) The far field intensity profile was extremely flat out to large angles [Fig. 2(c)], as expected from an isotropic emitter in the absence of significant surface refraction. With a substrate with an index matched or slightly higher than the organic (e.g., $n \sim 1.68$) and a larger lens, the total emitted light could be improved by as much as a factor of five. The factor of three improvement observed here is limited primarily by the finite extent of the lens, and the slightly lower index of refraction of the substrate than the organic layer.

In our work we have used large LEDs (diameter 1.75 mm) and large lenses (diameter ~few mm) for experimental simplicity. Clearly the results should scale if the glass thickness, lens diameter, and OLED diameter are all similarly reduced. Therefore, scaling to ~100 $\mu$m bottom-emitting OLEDs for small pixels would require thin substrates, such as plastic foils.[9,10] Further work is underway to implement this technique using planar lenses (e.g., Fresnel, thin film, etc...) and to compare our results with simple backside surface roughness.

In summary, a technique for increasing the total emitted efficiency of an OLED by at least a factor of three has been demonstrated with the patterning of features on the back of the substrate. To achieve maximum impact, one must not only capture light waveguided in the substrate, but also light waveguided in the organic/ITO layers, which we accomplished by using high-index transparent substrates. By adjusting the location of the center of curvature of the surface features, and the shape of the features, the far-field emission pattern can be tuned.

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