Enhanced light extraction efficiency from organic light emitting diodes by insertion of a two-dimensional photonic crystal structure

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We studied the characteristics of organic light emitting diode (OLED) devices containing two-dimensional (2D) SiO₂/SiN₄ photonic crystal (PC) layers. The finite-difference time-domain (FDTD) method was employed for the design and analysis of the PC OLED. Based on the design parameters derived from the FDTD calculations, a 2D PC layer was introduced on the glass substrate of a typical OLED structure by two-step irradiated hologram lithography and reactive ion etching. Experiments showed that incorporation of the PC layer improved the light extraction efficiency by over 50% compared to the conventional OLED, without noticeable degradation in electrical characteristics, under typical operating conditions. This improvement originates from the liberation of the photons trapped in the high-index guiding layers. © 2004 American Institute of Physics. [DOI: 10.1063/1.1815049]

I. INTRODUCTION

Organic light emitting diode (OLED) displays have been actively investigated in recent years on account of their potential applications in flat panel displays and flexible displays. The OLED is a very promising organic electronics component created by combining organic and inorganic materials, such as organic luminescent layers, organic electron-hole injection layers, a metal electrode, and a transparent oxide electrode. However, OLEDs have yet to be developed that meet the overall efficiency standards required by the industry. Various efforts have been made to improve the performance of OLEDs by elucidating the role, operating mechanism, and fabrication method of each of the organic and inorganic materials used to construct the OLED. Improving the luminous efficiency of OLEDs is the key issue that must be resolved if OLEDs are to be widely commercialized, because both low power consumption and long operational lifetime are required for mobile displays. The external quantum efficiency ηex of an OLED device is related to the internal quantum efficiency ηin and the light extraction efficiency ηext

ηex = ηin ηext.

The internal quantum efficiency ηin of OLEDs has been optimized such that it now approaches the theoretical limit. On the other hand, for thin-film structures, only a small fraction of the total photons generated inside the film are generally useable, because of the total internal reflection and wave-guiding effects of high-index layers. In fact, the light extraction efficiency of OLEDs constructed to date is typically only ~20% of the internal efficiency. Therefore, in order to further improve the external quantum efficiency, one has to find ways to increase the light extraction efficiency. Thus, if full-color-mobile OLED displays are to become commercially viable, the problem of low extraction efficiency must be overcome. Several out-coupling schemes have been implemented in the hope of improving light extraction from OLEDs. Recently, the insertion of a photonic crystal (PC) structure into the semiconductor slab LED structure was proposed and successfully implemented.

Prompted by those studies on semiconductor LEDs, we have devoted considerable research effort to apply a similar approach to OLEDs without degrading the spatial resolution of the display device. Very recently, we proved that the introduction of two-dimensional (2D) PC layers into OLEDs is an effective way to solve the light-trapping problem.

In this paper, we provide an overview of the optical consequences of introducing a 2D PC structure into an OLED. This article is organized as follows. In the first section, we summarize previous attempts to improve the extraction efficiency from OLEDs. In the second section, we describe the device architecture used in the simulations and experiments. Analyses based on the finite-difference time-domain (FDTD) method for the design of efficient PC OLEDs are also discussed. In the third part, we discuss the experimental procedure, results, analyses, and approaches that can be taken to optimize the effects of the integrated 2D photonic crystal patterns. Finally, we present our conclusions.

II. ENHANCEMENT OF LIGHT EXTRACTION EFFICIENCY

Various methodologies have been tried in the ongoing effort to improve the extraction efficiency of thin-film OLED
Analyses based on the quantum mechanical microcavity model suggested that external coupling efficiencies in excess of 50% should be possible for certain structures. This model was used to examine how the external efficiency varies with (i) exciton-to-cathode distance, (ii) the thickness of the indium tin oxide (ITO) layer, and (iii) the refractive index of the substrate in the normal OLED structure. A simple method for improving OLED extraction efficiency is to make the ITO layer sufficiently thin so that the formation of waveguide modes is prevented.

Simple dielectric capping of top-emitting OLED devices has also been proven to be effective for this purpose. Light emission from OLEDs can be understood in terms of interplay between two different interference effects. For example, the microcavity effect can modify the angular distribution of the emitted light, potentially making it possible to funnel more photons within a narrow angle of the normal direction. In addition to the two approaches outlined above (the addition of a layer and the modification of the layer thickness), other techniques have also been developed based on the perturbation of the guided light. These techniques can be divided into two main categories: (1) Reduction of the total internal reflection at the glass-air interface, and (2) modification of the relative number of organic layers to encourage the escape of the photons trapped in substrate modes (glass-guided modes) and the high-index guided modes.

One simple method to perturb the glass-guided mode is to increase the surface roughness at the substrate-air interface. In this case, photons that would normally undergo total internal reflection can escape from the glass by finding different incident angles upon the second reflection. In LED devices, this effect has been shown to increase the output coupling by as much as 50%. However, this scheme is not applicable to display applications because of the resolution problem. The use of microlenses attached to the front surface has been shown to be a successful method to extract the guided light from the glass substrate. Attaching an ordered array of 10 μm diameter microlenses to the glass substrate of an OLED has been shown to increase the light output of the OLED by a factor of 1.5–2.0 compared to the lens-free substrate. Shaping the device into a mesa structure has also been shown to increase the extraction efficiency by a factor of 2.0. Other simple techniques that have been used to perturb the substrate guided mode of OLEDs and thereby enhance the light output is the introduction onto the glass substrate of monolayers of silica spheres as a scattering medium. In another recent study on OLEDs, Tsutsui et al. showed that the external quantum efficiency could be doubled by incorporating a thin layer of very-low-index porous silica (n \sim 1.03) in the device. The techniques described above address the problem of enhancing the output coupling of the waveguide modes that are confined to the substrate.

The other major fraction of light generated from OLED source flows into the waveguide modes that are confined to the organic/ITO layers. If the problem of electrical leakage in OLED devices were less critical, the best way to reduce the high-index-guided modes would be to modify the optical structure at the ITO-glass interface. Several techniques based on this concept have been proposed to modify the distribution of optical modes in the organic/ITO layer.

A direct method to perturb both the ITO and the organic layer is by using a corrugated substrate, which induces a periodic undulation of the ITO/organic thin-film structure. The introduction of one-dimensional gratings with a period of several hundred nanometers has been shown to improve the extraction efficiency by a factor close to 2.0. Moreover, Hobson et al. found that further recovery of the trapped light could be provided by the surface plasmon with the help of a periodic grating formed on substrate. Gifford and Hall demonstrated that one-dimensional grating-assisted Ag surface plasmon cross coupling can be used to transmit organic photoluminescence and electroluminescence through an opaque silver layer. In reality, the modification of the guided light through the ITO/organic layer is of little practical use in electrically pumped OLEDs due to the strong effect of the surface roughness of ITO on the electrical properties of OLEDs. Therefore, to improve light extraction from OLEDs without causing the electrical problems associated with electrically pumped OLEDs, we introduced a 2D PC slab into the interface between the glass substrate and ITO layer. The introduction of a 2D PC into OLEDs to enhance the extraction efficiency of OLEDs is a different research area; hence in the present study we focused our attention on the physical background, fabrication processes, and display applications of 2D PC OLEDs.

### III. DESIGN OF THE PC OLED STRUCTURE

We used the FDTD method to model and design the OLEDs. The FDTD method has been shown to be very effective for modeling complex multilayer OLED devices in which the electron-transporting layer (ETL) is only a few tens of nanometers away from a metallic layer. Figure 1 shows a schematic diagram of the conventional OLED structure used in both the FDTD modeling and OLED fabrication in the present work. The conventional OLED is made up of a multilayer sandwich structure that comprises a glass substrate, an ITO anode, several organic emitting layers, and a metal cathode.

The FDTD calculations assume no optical losses from the organic/inorganic transparent layers, and that emitted light is reflected at the metal interface. The light emitting
excitons inside the OLED are modeled as 20 fs long Gaussian oscillating dipole pulses that have a center frequency of 530 nm and a full bandwidth at half maximum of 50 nm. Because the spatial distribution of excitons in real OLEDs is such that they can be termed as incoherent sources, the pulses used in the FDTD calculations will mimic the emission properties provided the spectral distribution is similar to that of the real source. In our FDTD calculations, sufficiently many dipole sources with equal numbers of mutually orthogonal $x$-, $y$-, $z$- polarizations were distributed randomly throughout the active area. In these calculations, the contribution of the surface plasmon mode was automatically included by using a complex refractive index $(n=0.867 + i6.49)$ of the Al electrode for both the conventional and PC OLED structures.\textsuperscript{29,30} The refractive indices of all of the layers of the conventional OLED used in the FDTD simulations are shown in Fig. 1.

As a first step, we calculated the extraction efficiency of a conventional OLED structure, using FDTD analysis. As mentioned above, the light emitted from an OLED device is funneled into three modes: the external propagation modes, the glass guided modes, and high-index guided (ITO/organic guided) modes. The light paths and the calculated fractions of the three modes are shown in Fig. 1. Previous calculations on Lambertian light sources with classical ray optics implied that the fractions of the energy in the air propagation, glass guided, and high-index guided modes are 0.2, 0.3, and 0.5, respectively.\textsuperscript{17} Recently, a quantum-mechanical weak microcavity theory was proposed to precisely calculate the efficiencies of each mode for OLED layered structures.\textsuperscript{16} According to our FDTD calculations, the external modes that escape the substrate make up only $\sim 26.4\%$ of the light emitted from the OLED device. The precise ratio of the three modes in OLEDs is dependent on the optical parameters of each organic or inorganic layer. Similar to the ray optics results reported previously,\textsuperscript{17} the FDTD findings indicate that the conventional OLED device has the low external efficiency and high trapping efficiency. For this OLED device, the two confined modes do not contribute to the extracted light because they are either absorbed by the various layers or emitted from the edge of the substrate; these modes must be minimized if high efficiency is to be achieved.

Previously we reported\textsuperscript{34} that the radiation profiles of both the horizontal dipole source $d_{x,y}$ and the vertical dipole source $d_z$ vary with the distance between the active layer and the metallic cathode $D_c$. Given that previous study showed that most of the radiation from the $d_z$ dipoles is emitted below the critical angle and thus cannot escape from the glass into the air, we concentrated on the in-plane dipoles $d_x$ and $d_y$. Note that since the image dipole of $d_{x,y}$ induced by the metallic cathode is out of phase with the original $d_{x,y}$, constructive interference was expected when $D_c = \lambda/(4n_{\text{ETL}})$. Clear enhancement of the vertical radiation was obtained for $D_c = 80$ nm, indicating that this thickness satisfies the condition for constructive interference. Thus, we confirmed that the optimal ETL thickness is about 80 nm. The thickness of the ETL and the position of the emitting layer are considered critical design parameters for OLEDs.

To enhance the extraction efficiency of the OLED, we introduced into the conventional OLED a 2D PC pattern made of two transparent materials of different refractive index $n$. As shown schematically in Fig. 2, the 2D PC layer was inserted at the interface between the glass substrate and the ITO electrode. The PC pattern was characterized by a lattice constant $A$ of 300–700 nm with a diameter $d$ of 150–500 nm and a height $h$ of 50–400 nm. The FDTD method was employed to estimate the contribution from the leaky modes and/or the diffraction modes of the 2D PC layer. The FDTD analyses showed that the light extraction efficiency depends on the structural parameters of the 2D PC pattern and the thickness of the over-coated high-index layer and ITO. It is thus desirable to design a 2D PC layer with dimensions that maximize the extraction efficiency of the OLED. It has been reported\textsuperscript{34} that, regardless of the depth of the pattern, there is a cutoff for the lattice constant $\Lambda_{\text{cutoff}}$ of about 200 nm, below which leaky waves remain trapped in the glass substrate. From the phase matching condition at the PC layer, the cutoff lattice constant can be expressed as follows:

$$\Lambda_{\text{cutoff}} = \lambda/(n_{\text{eff}} + 1),$$

where $n_{\text{eff}}$ is the effective refractive index of the PC layer $[n_{\text{eff}} = 1.7–1.8$ for a SiO$_2(n=1.48)$SiN$_x(n=1.95)$ PC layer]. In fact, we observed the same cutoff phenomenon in the FDTD calculations. We found that the extraction efficiency increases with the pattern depth, and takes on the largest values when the lattice constant is similar to the vacuum wavelength.

A detailed understanding of the modes and light paths produced in the OLED containing the 2D PC layer can be gained by studying the variation of the calculated intensity of propagating light as a function of time, which enables the creation of a light propagation diagram. Data were acquired for the system with incident light from a vertical dipole source. It has been reported that most of the radiation from vertical $d_z$ dipoles is emitted below the critical angle in organic light-emitting diodes, and thus cannot escape from the glass into the air.\textsuperscript{34} To confirm the effect of the introduction of a 2D PC structure on the light paths, it is best to examine the main components of the guided modes, such as the vertical dipoles. The calculation results are shown in Fig. 3 as gray-scale maps showing the energy density of the propagating wave. Immediately after the commencement of the emission process in the emitting layer, unguided light escapes from the glass substrate in both the conventional and 2D PC OLEDs. From the time dependence of the propagation path.
in the conventional OLED [Fig. 3(a)], it is clear that high-index guided light has little chance to leak into the glass substrate. The propagation diagram for the 2D PC OLED [Fig. 3(b)] shows the time dependence of the emission process, in which light is leaked by the corrugation in the leaky and/or diffraction modes. This diagram provides qualitative evidence of the enhancement of the time-integrated radiation power produced by the corrugated structure.

It is worth pointing out that in this computation the light emitting dipole pulses last only ~20 fs and the total photon number available from the pulses is finite and fixed. It is interesting to observe that the time-integrated photon energy extracted into the air increases asymptotically with time. The photons in the ultrashort pulses leak out of the waveguide as the guided photons propagate along the high-index layer. However, one cannot wait indefinitely to collect all the photons. In real OLED displays, the finite pixel size of the device places an upper limit on the photon pulse travel time after which all the photons are effectively outside a given pixel. One simple way to take this into consideration is use the values of the integration at the time when the photon generated at the center of a pixel arrives at the boundary of the pixel. To compare the extraction efficiency of OLEDs, a standard light propagation time of 400 fs, calculated as the average light propagation time needed to reach the boundary of a pixel of size 200 × 50 μm², is used. The extraction efficiency can be improved by 50%–80% by adjusting the structural parameters of the 2D PC slab and the pixel size.

IV. FABRICATION OF THE PC OLED STRUCTURE

The fabrication processes for 2D nanoarrays of low-index materials and 2D PC slabs have been described in detail elsewhere. The process used for coating low-index materials depends on both the refractive index of the material and the procedure used to prepare the material. Two different types of low-index materials—SiO₂ and silicate derivatives—were used in the present work. SiO₂ films were coated onto a glass substrate by plasma enhanced chemical vapor deposition (PECVD). Then, the photoresist (PR) film was spin coated on top of the low-index layer. The patterning of the 2D nanoray of low-index films was carried out using the interference method with two laser beams. A 325 nm linearly polarized HeCd laser was used as an irradiation source. Fabrication of a 2D periodic structure was carried out by first irradiating the substrate from one angle, and then rotating it by 90° and irradiating it a second time under the same conditions as the first irradiation. In this process, the intensity per exposure lies under the threshold for development, whereas the sum of the two exposures lies above this threshold. With positive PR, development resulted in a 2D square lattice pattern of rods or holes in the resist. The irradiated PR films were developed with tetramethylammonium hydroxide, and SiO₂ films masked with patterned PR films were etched with O₂ + CF₄ gas by using reactive ion etching. Then, low-index films with a square nanorod or nanohole pattern were obtained. Figure 4(a) shows scanning electron microscopy (SEM) images of a tilted cross-sectional view of the 2D nanorod patterns of low-index SiO₂. The nanorods of low-index material look regular and uniform. To form a 2D PC slab, a layer of a high-index material such as SiNₓ is PECVD deposited onto the 2D low-index nanoray. PECVD gives pure, homogeneous, planar, low-temperature processed films. Crack-free, thin SiN films are transparent and have relatively high refractive indexes (1.90–1.95). The image [Fig. 4(b)] of OLED containing a 2D PC slab shows that the fabrication procedure successfully achieved filling and planarization over the low-index dotted structure. As reported, high-index film coatings have rms surface roughness values of 40–50 Å, as measured by AFM topographic imaging. To further decrease the rms surface roughness of the 2D PC slabs used in the present work, we employed a chemical mechanical polishing (CMP) process with a silicate polishing slurry. After polishing, the OLED surface was acceptably smooth for the insertion of a 2D PC layer between the ITO layer and the glass substrate.

To investigate the effect of the 2D PC layer experimentally, we fabricated OLEDs on both a conventional substrate and a PC layer covered substrate, side by side for comparison. The ITO layer (thickness 150 nm) was deposited by rf magnetron sputtering with no intentional heating. The sheet resistance of the ITO was ~30 Ω/sq. The measured transmission of the ITO-deposited glass substrate at 530 nm was ~85%. This value agrees well with the transmission ob-
OLEDs were encapsulated with 0.7 mm Corning cover glass. stripes oriented at an angle of 90° to the ITO stripes. The thermal evaporation using a shadow mask with 3 mm wide thick LiF/Al cathode and the Al cap layer were formed by vacuum sublimation with an open mask. The 30–50 nm aluminum (Alq3)–coumarin 6(C6), and Alq3 were prepared by vacuum sublimation with an open mask. The 30–50 nm thick LiF/Al cathode and the Al cap layer were formed by thermal evaporation using a shadow mask with 3 mm wide stripes oriented at an angle of 90° to the ITO stripes. The OLEDs were encapsulated with 0.7 mm Corning cover glass. Figure 4(b) shows a focused ion beam-type SEM (FIB-SEM) image of the tilted cross-sectional view of the OLED with the 2D SiO2/SiNx PC layer. This image shows that the 2D SiO2/SiNx PC layer was successfully inserted at the interface between the ITO layer and the glass substrate to give an OLED device with the design shown in Fig. 2.

V. RESULTS AND DISCUSSION

We first investigated the EL of the conventional and 2D PC OLED devices to confirm that the inclusion of the 2D PC had given the predicted enhancement of extraction efficiency. We then measured the optical properties of the PC-containing OLEDs to assess their suitability for display applications.

EL analyses were carried out to study the electro-optical properties of the 2D SiO2/SiNx PC slab. Figure 5(a) shows the current density-luminance (right axis) characteristics of the OLEDs with and without the 2D SiO2/SiNx PC layer. The luminance values of the 2D PC and conventional OLEDs measured at the normal angle (θ=0°) under 20 mA/cm2 DC excitation were 3280 and 2180 cd/m2, respectively. Figure 5(a) also shows the relationship between the current efficiency and the current density of three OLEDs, the conventional OLED and 2D PC OLEDs with nanorod array periods of λ=350 and 500 nm. The current efficiency in the normal direction at 20 mA/cm2 of the conventional OLED was 10.9 cd/A. In contrast, the corresponding current efficiencies for the λ=350 nm 2D PC OLED was 16.4 cd/A and that of the λ=500 nm 2D PC was 14.6 cd/A, indicating that the efficiency along the normal direction is 52% and 35% higher in the OLEDs containing PCs. Figure 5(b) shows the I-V characteristics of the OLEDs with and without the 2D PC layer. The I-V curve of the OLED containing the 2D SiO2/SiNx photonic slab is very similar to that of the conventional OLED, due to the improved flatness of the PC slab achieved by CMP. The similarity of the electron injection characteristics of the conventional and 2D PC OLEDs demonstrates that the techniques used to introduce the 2D SiO2/SiNx PC layer into the OLED are electrically acceptable. The results also clearly confirm that the insertion of the 2D PC layer between the ITO layer and glass substrate improves the external efficiency of OLEDs.

The emission spectra measured at constant current density (20 mA/cm2) for the conventional OLED and two PC OLEDs (lattice constant, λ=350 and 500 nm) are shown in Fig. 6. The results show that, at the main peak wavelength, the 2D PC OLEDs exhibit much stronger spectra than the conventional OLED. Moreover, the EL spectra of the two 2D PCs are very different, indicating that the 2D PC effect and therefore the structure parameter influence the spectral characteristics. For the conventional OLED, the EL is greatest at 520 nm. A simple analysis based on grating scattering can be applied to the 2D PC layer at the interface between the ITO layer and the glass substrate.

![EL analyses of OLEDs with and without a 2D PC layer.](image1)

![Emission spectra of OLEDs with and without a 2D PC layer at the interface between the glass layer and the ITO electrode.](image2)
into the air when the wave vector of the guided mode at the 2D PC layer \((k_{\text{eff}})\) becomes smaller than \(k_{\text{glass}}\). Bragg scattering is governed by the following equation:

\[
k_{\text{eff}}(\lambda) = 2 \pi n_{\text{eff}} \lambda.
\]

\[
|\vec{k}_{\text{glass}}(\lambda)| > |\vec{k}_{\text{eff}}(\lambda) \pm m \frac{2 \pi}{\Lambda} i \pm n \frac{2 \pi}{\Lambda}|
\]

where \(m\) and \(n\) are integers, \(n_{\text{eff}}\) is the refractive index of the 2D PC layer, \(\lambda\) is the wavelength at which the EL intensity of the OLED is greatest, and \(\Lambda\) is the lattice constant of the 2D PC. The Bragg scattering modes produced by the 2D PC provide a simple set of characteristics on which to base efforts to enhance the extraction efficiency of OLEDs. Equation (3) indicates that the lattice constant of the 2D PC strongly influences the peak shape of EL spectra such as those shown in Fig. 6. However, although the scattering characteristics can be used as a guide to enhance the extraction efficiency and to alter the emission spectrum, Bragg scattering alone cannot explain the peak shape of the emission spectrum of a 2D PC OLED. In addition to the Bragg scattering and/or leaky modes of a PC, the interference effects of weak microcavity are also believed to influence the emission spectrum of 2D PC OLEDs. The correlation between the emission spectrum and the structural parameters of a 2D PC OLED is considerably more complex. To explain the emission spectra from 2D PC OLEDs qualitatively, the microcavity modes as well as the leaky and/or Bragg scattering modes must be considered.

We additionally examined the angular dependence of the emission spectrum because variation in the color with changing viewing angle is undesirable for display applications. Figures 7(a) and 7(b) show the angle dependence of the emission spectra of a conventional OLED and a 2D PC OLED at room temperature, respectively. The results show negligible angle dependence in the peak shape of the conventional OLED, but some variations in the emission spectrum of the 2D PC OLED. The perceived color of the emission spectrum was expressed in terms of the chromaticity coordinates developed by the Commission Internationale de’Eclairage (CIE). CIE coordinates were utilized to assess the color changes in the OLEDs. Figure 8 shows the angular dependence of CIE color coordinates for the conventional OLED and the 2D PC green OLED \((\lambda=350\ \text{nm})\) on a chromaticity diagram. When viewed from the normal direction, the CIE color coordinates for the conventional OLED and 2D PC green OLED are \((0.306, 0.642)\) and \((0.278, 0.666)\) respectively. This indicates that the light emitted by the 2D PC OLED is of much higher color purity than the conventional standard. The results additionally show that, as the viewing angle is changed over angles up to 70° of normal, the color change ratio of the 2D PC OLED \((\Delta x=6.2\%, \Delta y=3.3\% )\) is similar to that of the conventional OLED \((\Delta x=7.6\%, \Delta y=2.0\%)\). Improved color purity is therefore another advantage of 2D PC OLEDs over conventional OLEDs. Further improvement of color purity and angular dependence can be achieved by tuning the structural parameters of the 2D PC slab.
fold symmetry, resulting from the square lattice pattern with fourfold symmetry. The measured 2D far-field radiation pattern of the 2D PC OLEDs can be explained by the simulated 2D pattern obtained by FDTD based simulation. The details of this computational analysis are given elsewhere. The relationship between the experimental and computational diffraction fringes consistently indicates that the 2D far-field relationship between the experimental and computational patterns. The far-field profiles cut along the horizontal line 500 nm gives rise to a complex intensity profile that comprises a mixture of concentric square, circle, and cross patterns. The far-field profiles cut along the horizontal line (A-B) are plotted in Figs. 9(d), 9(e), and 9(f). Comparison of these profiles reveals that the angle of maximum intensity of emitted light depends strongly on the lattice constant of the 2D periodic structure. Therefore, the far-field images of 2D PC OLEDs are complex due to mixing of the effects of Bragg scattering modes and weak microcavity modes.

To compare the extraction efficiencies of the conventional and PC OLEDs, we calculated the total amount of emitted light over all angles by using an integration sphere. As shown in Table I the PC OLEDs show enhanced extraction efficiencies relative to the conventional OLED. This enhancement of the total amount of emitted light is somewhat different from that in the extraction along the normal direction, because the integrated value includes contributions from the anisotropic diffraction fringes in the far-field radiation patterns of the PC OLEDs [Figs. 9(b) and 9(c)]. In addition, although the amount of light emitted in the normal direction simply decreased with increasing the lattice constant from 350 to 500 nm, the integrated values for the two PC OLEDs showed a more complex relationship. For low viewing angles with respect to the substrate surface normal, the 350 nm PC OLED gives a larger integrated extraction efficiency than the 500 nm PC OLED. At other viewing angles, however, the opposite behavior is observed. Therefore, the far-field profile of 2D PC OLEDs is an important determinant of whether such devices can be used in display or lighting applications.

To evaluate the reliability of the 2D PC OLED, DC lifetime measurements under accelerated conditions (50 mA/cm²) were performed on a PC OLED (A =350 nm) and a conventional OLED (Fig. 10). The initial luminescences of the PC OLED and the conventional OLED were 8400 and 5500 cd/m², respectively. It is apparent that the insertion of a 2D SiO₂/SiNₓ PC layer into an OLED does not alter the aging rate. This result implies that the slight change in surface roughness produced by the insertion of the 2D SiO₂/SiNₓ PC layer has little effect on the aging process. This reliability test and the EL data demonstrate that the fabrication technique described above for introducing a 2D SiO₂/SiNₓ PC layer into an OLED is electrically acceptable and commercially viable.

VI. CONCLUSION

We have studied the effects of the 2D PC layer inserted in an OLED with the aim of increasing its extraction efficiency. First we used the FDTD method to calculate the extraction efficiency while varying the lattice constant, depth, and rod size. Introduction of a PC layer into the OLED structure was demonstrated to be an effective way to liberate the photons trapped within the organic ITO waveguide layer. The theoretical predictions of the FDTD calculations were confirmed through the realization of highly efficient OLEDs containing a 2D PC. Two-step irradiated hologram lithography and reactive ion etching were used to create a 2D PC pattern on the glass substrate. To date, the maximum enhancement of the extraction efficiency of an electrically pumped PC OLED that has been achieved is about 50%.

**TABLE I.** Measured relative extraction efficiency of a conventional OLED and two PC OLEDs (A=350 and 500 nm).

<table>
<thead>
<tr>
<th></th>
<th>Conventional OLED</th>
<th>PC OLED A=350 nm</th>
<th>PC OLED A=500 nm</th>
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</thead>
<tbody>
<tr>
<td>Relative efficiency</td>
<td>100%</td>
<td>152%</td>
<td>135%</td>
</tr>
<tr>
<td>normal (θ=0°)</td>
<td>(10.9 cd/A)</td>
<td>(16.4 cd/A)</td>
<td>(14.6 cd/A)</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>100%</td>
<td>141%</td>
<td>155%</td>
</tr>
<tr>
<td>integrated sphere</td>
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FIG. 9. (a-c) Measured 2D far-field intensity profiles of (a) a conventional OLED, (b) a PC OLED (A=350 nm), and (c) a PC OLED (A=500 nm). (d-f) Intensity profiles along the horizontal line (A-B) of the 2D far-field intensity profiles for (d) a conventional OLED, (e) a PC OLED (A=350 nm), and (f) a PC OLED (A=500 nm).

FIG. 10. Normalized EL intensity at 50 mA/cm² as a function of aging time of the conventional OLED (dotted line), and of the OLED containing a 2D PC layer (solid line).
However, we believe that further improvement in the OLED efficiency and the far-field radiation pattern can be achieved by optimizing 2D PC OLED structural characteristics such as the period, depth, filling factor, and refractive index of the 2D low-index material dotted array, the thickness and degree of planarization of the high-index layer, and the reflectivity of the anode metal mirror.

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