Hindawi Publishing Corporation
Journal of Nanomaterials
Volume 2013, Article ID 969120, 6 pages
http://dx.doi.org/10.1155/2013/969120

Research Article

The Effect of Anisotropy on Light Extraction of Organic Light-Emitting Diodes with Photonic Crystal Structure

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Received 31 January 2013; Accepted 10 March 2013

Academic Editor: Yongfeng Luo

The light extraction efficiency of organic light-emitting diodes (OLED) is greatly limited due to the difference in refractive indexes between materials of OLED. We fabricated OLED with photonic crystal microstructures in the interface between the glass substrate and the ITO anode. The light extraction efficiency can be improved by utilizing photonic crystals; however, the anisotropy effect of light extraction was clearly observed in experiment. To optimize the device performance, the effect of photonic crystal on both light extraction and angular distribution was investigated using finite-difference time domain (FDTD) method. We simulated the photonic crystals with the structure of square lattice and triangle lattice. We analyzed the improvement of these structures in the light extraction efficiency of the OLED and the influence of arrangement, depth, period, and diameter on anisotropy. The optimized geometric parameters were provided, which will provide the theoretical support for designing the high performance OLED.

1. Introduction

Organic light-emitting diodes (OLED) have drawn much attention due to their potential applications in flat panel displays [1]. The basic structure of a conventional OLED is composed of glass substrate, Indium tin oxide (ITO) transparent conducting layer, hole transport layer, organic light-emitting layer, electron transport layer, and on the top of the device metal cathode. Luminous efficiency is one of the important indicators to measure the performance of OLED. The luminous efficiency is mainly determined by the quantum efficiency which is divided into internal quantum efficiency η_{int} (the ratio of the total number of photons generated within the organic emitter to the number of injected electrons) and external quantum efficiency η_{ext} (ratio of the total number of photons emitted by the OLED into the viewing direction to the number of electrons injected into organic emitter). The ideal solution to increase η_{int} has been proposed and the internal quantum efficiency can be reached near 100% [2], while the external quantum efficiency is dependent not only on η_{int} but also on the external coupling efficiency η_{coupling} (the ratio of the total number of photons coupled out in the forward direction to the total number of photons generated within the organic emitter). The external coupling efficiency is also called light extraction efficiency. So we can get the following expression [3]:

$$\eta_{\text{ext}} = \eta_{\text{int}} \cdot \eta_{\text{coupling}}. \tag{1}$$

However, the light extraction efficiency still needs to be improved due to the restriction of mismatch of refractive index between the substrate and organic materials on the energy of the guided wave. This kind of mismatch can cause such a low light extraction efficiency that only 20% of light is extracted into air [4]. The mismatch of refractive index between ITO and glass (substrate) interface is the most serious. A great many measures have been taken to improve the light extraction efficiency of OLED [5–8].

It has been demonstrated that photonic crystal (photonic crystal) is an effective way to improve light extraction efficiency of OLED. After utilizing micro/nanostructures such as photonic crystal, the mismatch of refractive index between layers can be reduced to some degree and more light will be extracted into air because of the scattering of the photonic crystal structure [9, 10]. However, to optimize the device performance, not only light extraction efficiency but also angular distribution should be considered [11–13].

The mechanism of improving light extraction after utilizing photonic crystal has been proposed [9, 10]. In this

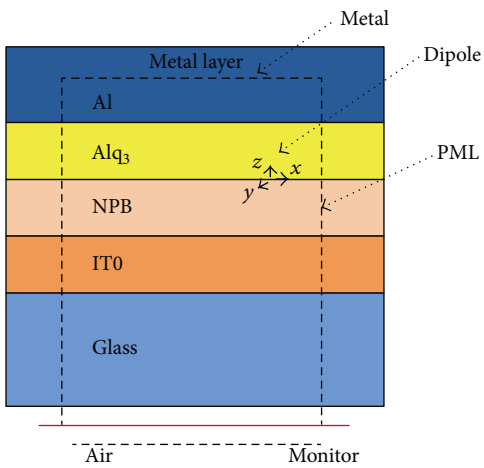


Figure 1: Simulation model of OLED.

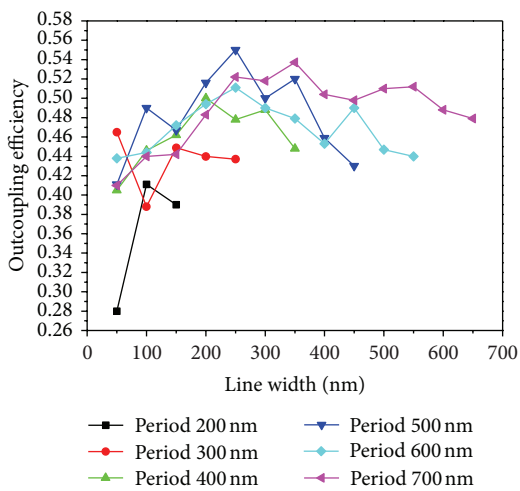


Figure 2: Parameter sweep of photonic crystal in green OLED.

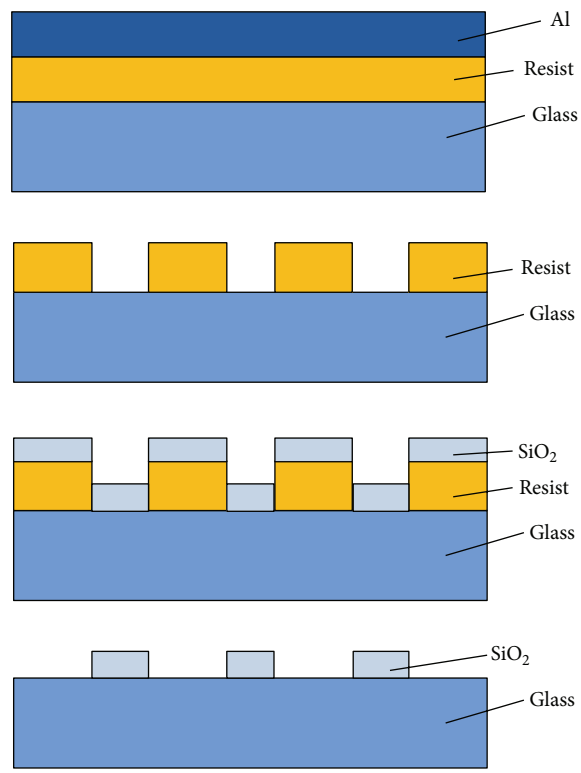


Figure 3: The fabrication procedure of SiO_2 pillars on glass.

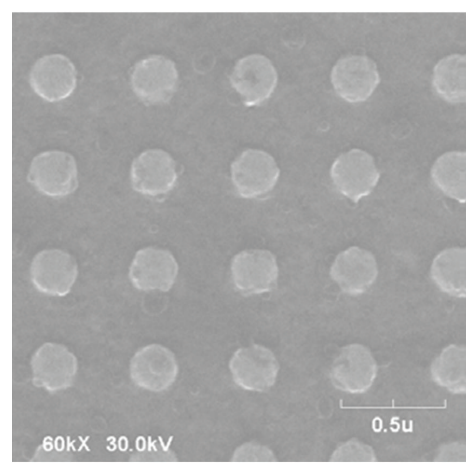


Figure 4: The photograph of the fabricated substrate.

paper, experimental and theoretical studies on the light extraction and anisotropic effects were addressed. Firstly, the parameters of photonic crystal were optimized to achieve the best light extraction efficiency by using finite-difference time domain method. Secondly, experiment of luminance of OLED has been done to compare photonic crystals of different structures. We studied the far field of the devices by using FDTD and ASAP ray tracing software and discussed the influence of arrangement, depth, period, and diameter on anisotropy. The anisotropy of light emitted from the devices has been observed from experiment.

The simulated model of the device is shown in Figure 1, in which we keep the substrate small enough to simulate multiple round trips of light. In addition, the substrate should be modeled large enough so that the near-field optics effect wouldnot happen. Also, we minimized the size of the device by using perfect match layer boundary; in this way we neglect the leakage and reflection of light from the edge of the device.

In our case, a series of green OLED with different period and diameter of photonic crystal was modeled, from which we obtained different outcoupling efficiencies. The optimum value of the green device is period of 500 nm, diameter 300 nm. The parameters of photonic crystals of the devices can be optimized by parameter sweep in FDTD, shown in Figure 2.

2. Experiments

In the experiment, the former optimized photonic crystal pattern (500 nm period, 250 nm line width) and an unoptimized photonic crystal pattern (200 nm period, 100 nm line width)

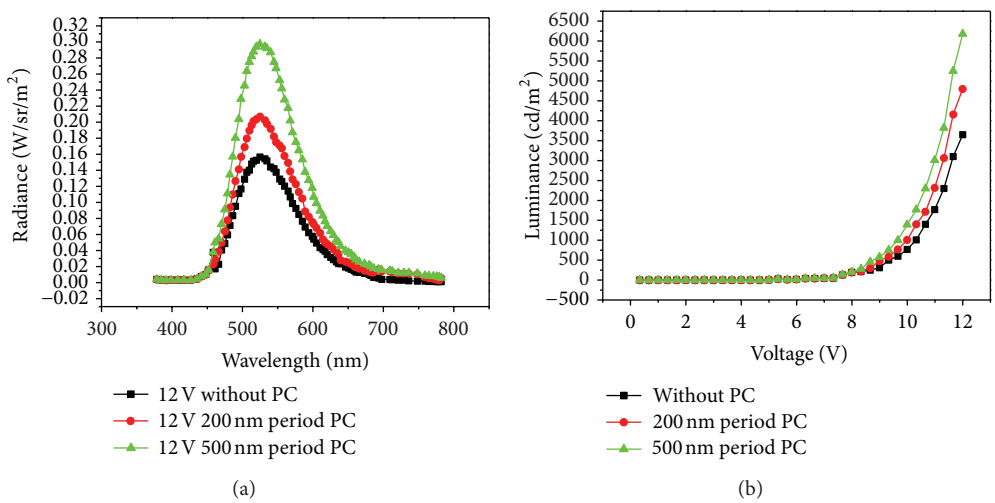


Figure 5: (a) The measured spectra of the OLEDs; (b) characteristic of luminance versus voltage.

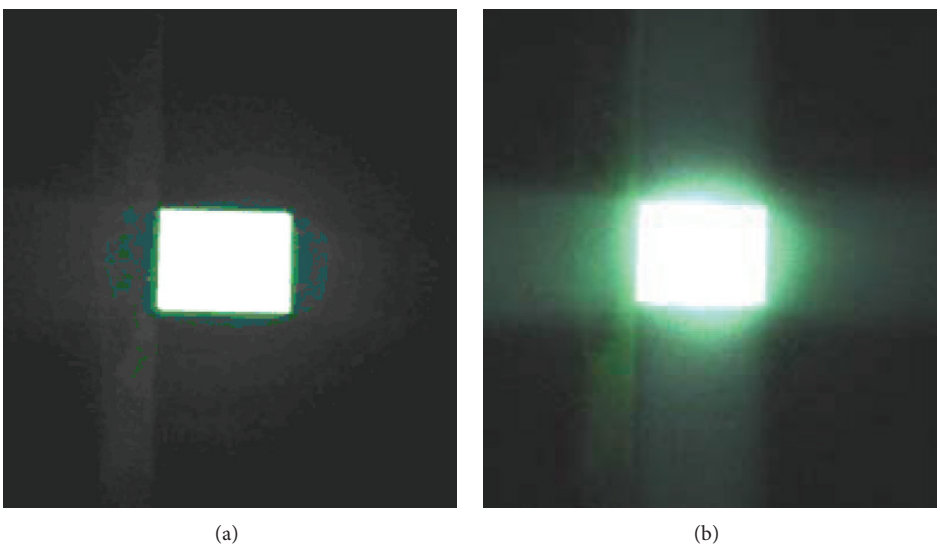


Figure 6: The comparison of OLED with photonic crystal and without photonic crystal.

were formed on a glass substrate by IC technique. The SiO_2 pillars on glass can be fabricated as follows, which is shown in Figure 3. Firstly, a 350 nm electron beam resist was spinned on glass. A 30 nm Al which acted as conductive layer in the process of electron beam lithography (EBL) was evaporated on the top. After EBL, the patterns on resist can be formed. Finally, we sputtered SiO_2 of 300 nm thick and lifted off the resist to get the SiO_2 pillars. The photograph of the fabricated substrate is shown in Figure 4.

SiNx buffer layer was sputtered on the substrate with SiO_2 pillars; then the ITO anode was deposited and annealed in order to make the resistivity low; after that, organic and cathode layers were deposited on the top to fabricate the complete device.

The organic layers and the cathode LiF/Al were sequentially deposited by conventional vacuum vapor deposition in the same chamber without breaking the vacuum. The pressure of the chamber was 1×10^{-6} Torr. The structure of the device with the thickness of every layer is given as follows: ITO/NPB (30 nm)/Alq_3 (50 nm)/LiF (0.5 nm) Al (100 nm). The thickness of the organic layers was measured by using quartz-crystal monitors.

The electroluminescent (EL) spectra and the CIE color coordinates were measured by using Pro-650 Spectra Scan, and the current-voltage (I-V) characteristics were measured using Keithley 2400 Source Meter and LS110Minolta luminance meter.

3. Results and Discussion

The measured spectra and the characteristic of luminance versus voltage of the devices are shown in Figures 5(a) and 5(b), respectively, both of which were driven at 12 V at room temperature. from the figures we can see that the peak in

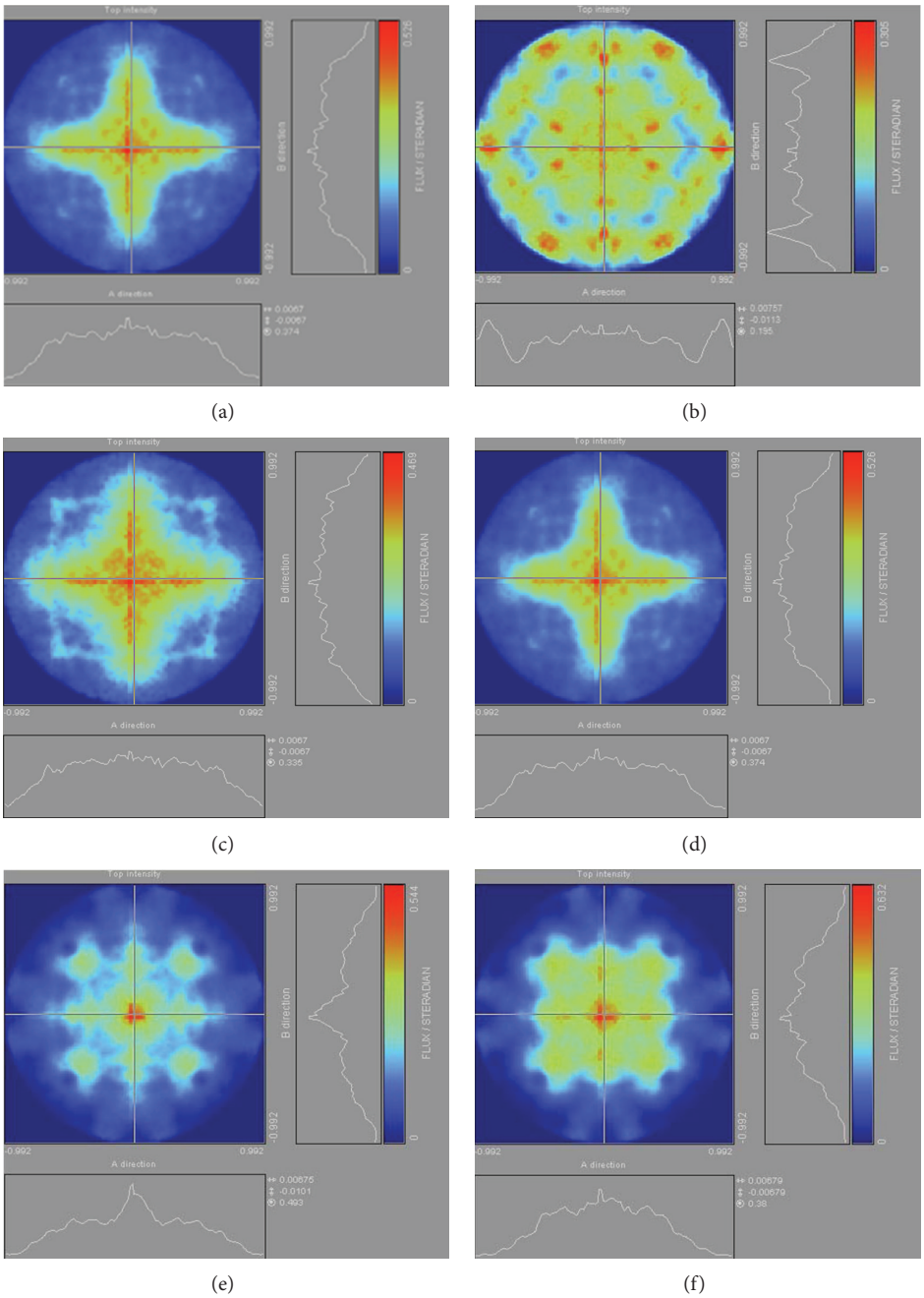
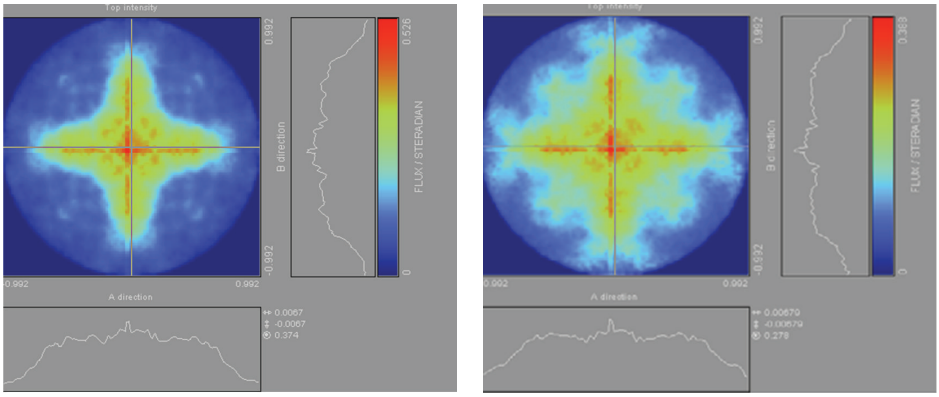


Figure 7: (a) Square lattice, (b) triangle lattice, (c) 200 nm depth, (d) 300 nm depth, (e) 400 nm depth, and (f) 500 nm depth.

spectrum is 520 nm, and the value of radiance with photonic crystal is higher than that without photonic crystal. When the parameters are closer to the optimal, the value of radiance and luminance reaches the highest.

From the experimental result we can find that although the outcoupling efficiency of the devices was enhanced after introducing photonic crystal structure, the light emitted from the devices with photonic crystal structures becomes less uniform than that without photonic crystal structures. The comparison of OLED with photonic crystal and without photonic crystal was shown in Figure 6.

Therefore, it is necessary to study the effect of photonic crystal on anisotropy of the light emitted by means of simulation. In fact, the simulation of the complete OLED device is a cross-scale simulation [14]. Considering the anisotropy of light extraction, we neglected the multiple scattering part of light so as to get the direction and the intensity information of light which just passes through the photonic crystal structures. Then this information can be loaded to ASAP to trace the propagation of light in substrate. Finally, the far-field information can be obtained.



(a) (b)

Figure 8: (a) 500 nm period 250 nm diameter; (b) 200 nm period 100 nm diameter.

From Figure 7 we can see the distribution of light extraction copy distribution effect on the photonic crystals. When square lattice was implemented, the extraction would be cross-shaped. When triangle lattice was implemented, the extraction would be hexagonal shape. Figure 8 shows the shape similar to far field when the depth of photonic crystals changes. The bar on the right of each photo denotes the maximum difference of intensity, ranging from 0.469 to 0.526, 0.544, and 0.632 with the depth changing from 200 nm~500 nm, respectively.

It can be concluded that the intensity nonuniform increase as the structures become bigger. However, it is found that despite the X, Y direction, the light is extracted at 45° and 135° when the depth of photonic crystal increases. So the anisotropy will become less as the directions of extraction increase. The two factors compete with each other, so when the depth increases, the anisotropy first increases and then decreases. Therefore, the closer the period of the structure line width to the size of the optimum light efficiency structure, the more obvious the unevenness of the angle.

4. Conclusion

We can conclude that the enhancement of light extraction efficiency can be improved when the parameters of photonic crystal structure are closer to the optimal value; however, the anisotropy did exist when utilizing photonic crystals in OLED. The anisotropy effect becomes apparent when the period and diameter become closer to the optimal value. Therefore, the light extraction efficiency and anisotropy should be both considered to choose the suitable parameter of photonic crystal.

Conflict of Interests

FDTD and ASAP are two kinds of software. FDTD is mainly used to study the light whose wavelength is from tens of nanometers to a few hundred nanometers. In this paper, FDTD is used to analyse the layers from organic layers to glass substrate. ASAP is mainly used to study the light whose wavelength is in the range of geometrical optics (generally more than 1000 nm). In this paper, ASAP is used to analyse the scope from substrate to the air. The scope of application between them is different. The authors' group has bought the two softwares.

Acknowledgments

This research is financed by Guangdong Natural Science Foundation (Grant no. 10452902001005900), The China Postdoctoral Fund (Grant no. 20090461297), Guangdong Natural Science Foundation (Grant no. S2011040005742), Guangdong Provincial Science and Technology Innovation Project, Guangdong Province (2012KJCX0100), and Jiangmen City Science and Technology Project (2011010049758).

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