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High-performance green phosphorescent top-emitting organic light-emitting diodes based on FDTD optical simulation

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ABSTRACT

We have successfully applied finite-difference time-domain (FDTD) method in top-emitting organic light-emitting diodes (TOLEDs) for structure optimization, demonstrating good agreement with experimental data. A mixed host with both hole transport and electron transport materials is employed for the green phosphorescent emitter to avoid charge accumulation and broaden the recombination zone. The resulting TOLEDs exhibit ultra-high efficiencies, low current efficiency roll-off, and a highly saturated color, as well as hardly detectable spectrum shift with viewing angles. In particular, a current efficiency of 127.0 cd/A at a luminance of 1000 cd/m^2 is obtained, and maintains to 116.3 cd/A at 10,000 cd/m^2.

1. Introduction

Interest in next-generation displays technologies has stimulated research on active-matrix organic light-emitting diodes (AMOLEDs) [1,2]. In the design of AMOLEDs, the top-emitting structure permitting the light to emit through the top electrode is preferred due to its favorable merits, such as high aperture ratio, high pixel resolution, and low power consumption. This is desirable for AMOLEDs with underneath wirings and transistors [3,4].

Recently, many efforts have been made to improve the performance of TOLEDs. And most of them focused on adopting a classical analytic method to design device structures and various interface modifications to improve both optimum optical characteristics and electrical properties [5,6]. However, the classical analytic method is no longer applicable for the comparatively complex structure, while finite-difference time-domain (FDTD) method is a powerful simulation tool for complex OLED designs since this method is virtually applicable to any type of structure [7]. Additionally, phosphorescent light-emitting materials were widely used to improve the efficiencies of OLEDs since they can use triplet excitons for light emission and have a theoretical maximum internal quantum efficiency of 100% [8,9]. Nevertheless, since the triplet excitons will self-quench through triplet–triplet annihilation (TTA) or triplet–polaron annihilation (TPA) at high excitons densities, it is still a significant challenge to maintain a relative high efficiency at high luminance [10]. For example, Najafabadi et al. [11] reported a highly efficient green-phosphorescent top-emitting OLED with a current efficiency of 94 cd/A at a luminance of 1000 cd/m^2, but it

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dropped to 76 cd/A at 10,000 cd/m^2. In 2013, the same group further published an inverted top-emitting phosphorescent OLED with a current efficiency of 110 cd/A at 1000 cd/m^2 by adopting a novel Ag/HAT-CN/TAPC anode structure [12]. However, the spectra changed a lot over different viewing angles, which is a serious problem for display application. It is still a big challenge to fulfill all these requirements.

In this paper, we present high-performance green top-emitting phosphorescent OLEDs with a simplified tri-layer structure. The optical properties, such as spectra, relative outcoupling efficiencies, and angular distribution profile predicted by FDTD simulation are in good agreement with the experimental results, showing that FDTD is a powerful simulation tool for TOLED. By optical and electrical optimization, the devices with a highly saturated color and weak angle dependence have been realized. Furthermore, the optimized device achieves a high current efficiency of 127.0 cd/A at a luminance of 1000 cd/m^2, and maintains to 116.3 cd/A at 10,000 cd/m^2, which is 2.7 times as high as that of traditional bottom-emitting OLED (BOLED).

2. Experimental

Substrates of glass were cut into 2.5 × 2.5 cm^2 squares and were cleaned successively using detergent, acetone, and isopropanol in an ultrasonic bath. The substrates were treated for 15 min in each solvent and then blown dry with nitrogen gas. Then, a 150-nm-thick patterned Al layer was deposited onto the glass substrates as an anode in a high-vacuum electron beam evaporation system under a base of below 3 × 10^{-5} Torr. The samples were then transferred to a vacuum thermal evaporator and the chamber was pumped down to a base pressure of 5 × 10^{-5} Torr. A 3-nm-thick MoO_3 was first deposited on patterned Al coated glass substrates followed by all organic layers which were subsequently deposited at a rate of 0.5–1 Å/s.

The detailed device (Device A, B, C) structures are depicted in Fig. 1, where 1,3-bis(carbazol-9-yl)benzene (mCP) is as the hole transport layer (HTL), as well as light emitting host. 4,4′-bis(N-(1-naphthyl)-N-phenyl-amino) biphenyl (NPB) is another kind of hole transport material, while 4,7-diphenyl-1,10-phenanthroline (Bphen) is as the electron transport layer (ETL). 1,3,5-tris(N-phenylbenzimidazole-2-yl)benzene (TPBi) is a light emitting host material with predominant electron transport property, and iridium(III)bis(2-(4-trifluoromethylphenyl)pyridine) tetraphenylimidodiphosphinate (Ir(tfmppy)$_2$(tpip)) [13] is a green phosphorescent dye and as the emission layer (EML). The doping concentration of Ir(tfmppy)$_2$(tpip) in mCP and co-host is 6 wt% and the ratio of mCP:TPBi in co-host is 1:1 in device C. MoO_3 (3 nm) and the bi-layer structure 8-hydroxyquinoline lithium (Liq) (1 nm)/Al (1 nm) are utilized as hole and electron injection layer, respectively. To extract additional light from the devices and achieve both appropriate reflectivity and low absorption of the top contact for major emission wavelength of Ir(tfmppy)$_2$(tpip), an 80-nm-thick capping layer (CL) of mCP was deposited on top of the Ag. Fig. 2 shows the molecular structure of Ir(tfmppy)$_2$(tpip) and the energy level diagram extracted from the literatures [13–15].

The current density–voltage–luminance characteristics were measured by a computer controlled Keithley 2400 programmable voltage–current source and Topcon BM-7A Luminance Colorimeter. The emission spectra at different angles were measured with a calibrated Labsphere CDS 610 spectrometer by placing the TOLEDs on a rotating stage. All the measurements were carried out at the room temperature under ambient atmosphere.

3. Results and discussion

For effective design of devices, we have simulated the light emission profile using FDTD method, which allows for calculation of broad band emission in one run [7]. To match the random orientation and emission behavior of evaporated small molecules, we set three independent orthogonal dipoles and averaged the intensities in air. Fig. 3(a) sketches the cross section of BOLED and TOLED studied here. In the simulation, the refractive indices of organic materials and glass were assumed to be 1.77 and 1.51 over the wavelength of interest, respectively [16]. The complex refractive indices of the metallic electrodes and indium tin oxide (ITO) were taken from Refs. [17] and [18], respectively. We achieve an optimized configuration of optics for the TOLEDs shown in Fig. 1 via varying the length of the cavity and the location of the active layer in FDTD simulation. Fig. 3(c and d) shows the emission profiles of BOLEDs and TOLEDs calculated by FDTD, respectively, in which the TOLEDs' spectral radiance energy is

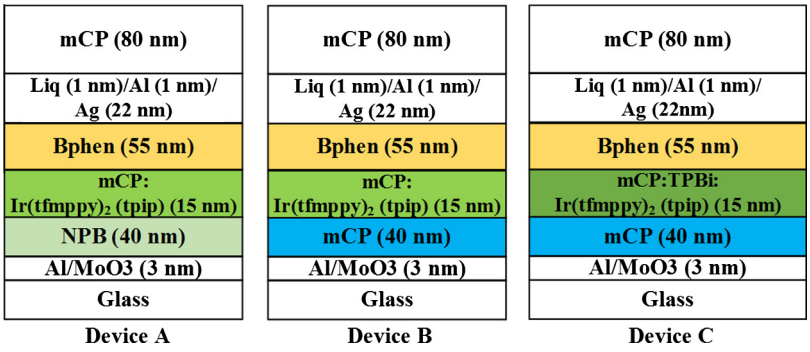

Fig. 1. Schematic device structures in this study.