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COMMUNICATION

Dual-periodic-microstructure-induced color tunable white organic light-emitting devices

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Abstract In this paper, we demonstrate a color tunable white organic light-emitting devices (WOLEDs) based on the two complementary color strategies by introducing two-dimensional (2-D) dual periodic gratings. It is possible to tune the color in a range between cold-white and warm-white by simply operating the polarization of polarizer in front of the microstructured WOLEDs. Experimental and numerical results demonstrate that color tunability of the WOLEDs comes from the effect of the 2-D dual periodic gratings by exciting the surface plasmon-polariton (SPP) resonance associated with the cathode/organic interface. The electroluminescence (EL) performance of the WOLEDs have also been improved due to the effective light extraction by excitation and out-coupling of the SPP modes, and a 39.65% enhancement of current efficiency has been obtained compared to the conventional planar devices.

Keywords dual periodic grating, surface plasmon-polariton (SPP), color tunable, white organic light-emitting devices (WOLEDs)

1 Introduction

White organic light-emitting devices (WOLEDs) have been actively investigated owing to their advantages, such as light weight, material abundance, low cost, low power consumption, and flexibility [1–4]. WOLEDs are highly promising candidates for next-generation lighting sources to replace conventional incandescent bulbs and fluorescent lamps [5]. An operating color tunable chromaticity of WOLEDs is required for their application of solid state lighting, especially for indoor applications [6–8]. For example, we can freely choose the most appropriate color of the lighting sources while doing various activities. By systematically modified the chemcial strucures of the organic materials of WOLEDs, color tuning with the driving voltage can be effectively achieve [9–12]. However, a simple and efficient way to achieve color tunable WOLEDs without special material design is still a challenge, which is an obstacle for the applications in solid state lighting.

In this communication, a color tunable WOLEDs based on the two complementary color strategies has been achieved by simply introducing a two-dimensional (2-D) dual periodic grating on the substrate. The 2-D microstructures consist two sets of corrugations with different periods, and have the effect to excite the surface plasmon-polariton (SPP) resonance associated with the cathode/organic interface of the WOLEDs. The blue and orange emissions trapped in the SPP modes associated with the electrode/organic interfaces are both efficiently extracted from the WOLEDs by adjusting appropriate periods of the dual periodic gratings. Because of the polarization characteristics of extracted light from the SPP modes, the color tunability of the WOLEDs has been achieved by simply operating the polarization of polarizer in front of the microstructured WOLEDs to vary the relative mixing ratio of the orange and blue portions. The emitting color of the WOLED is tuned from standard-white to cold-white and warm-white. By engaging the 2-D dual periodic graings, the electroluminescence (EL) performance of the WOLEDs have been effectively improved and a 39.65% enhancement in the current efficiency compared to those of the conventional planar devices has been obtained.

2 Experimental details

2.1 Preparation of the dual periodic gratings

The 2-D dual periodic gratings have been fabricated by the

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holographic lithography technique [13]. The photoresist (SU-8 2025, MicroChem Inc.) was diluted by cyclopentanone into 40 mg/mL, and was spin-coated onto the glass substrates which were pre-cleaned using standard procedure. The thickness of the SU-8 film was about 90 nm by controlling the spin speed of the spin coater at 5000 r/min as well as the spin time in 30 s. We used a UV laser (Coherent Inc.) with the wavelength of 266 nm as the irradiance light source. The glass substrates covered with SU-8 photoresist film were exposed for the first time by two beams interference split from the UV laser, and the photoresist film was exposed for the second time after rotating 90°. The beam size was 6 mm in diameter. After baking the exposed substrates at 95°C for 15 min and soaking in developing solution (acetone) for 2 min, the dual periodic gratings were finally formed on the substrates. The morphologies of the microstructures have been measured by an atomic force microscopy (AFM, Dimension Icon, Bruker Corporation) in tapping mode.

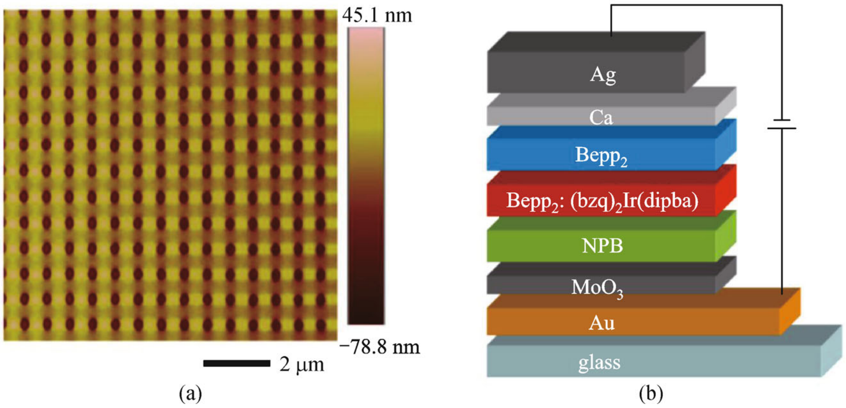
2.2 Fabrication and evaluation of the WOLEDs

A 15 nm Au film as the anode of the WOLED was deposited on the microstructured substrates in a thermal evaporation chamber at a base pressure of 5×10^{-4} Pa. A quartz crystal oscillator was used to monitor the deposition rate and film thickness of the deposited material. We then deposited 5 nm MoO_3 as the anodic buffer layer, 40 nm *N*,*N*′-diphenyl-*N*,*N*′-bis(1,1′-biphenyl)-4,4′-diamine (NPB) as the hole-transporting layer, 20 nm bis(2-(2-hydroxyphenyl)-pyridine)beryllium) ($Bepp_2$) with 2% wt bis(7,8-benzoquinolinato)iridium(III) (*N*,*N*′-diisopropyl-benzamidine) ($(bzq)_2Ir(dipba)$) as the emitting layer, 45 nm $Bepp_2$ as the electron-transporting layer, and LiF (1 nm)/Ag (100 nm) as the cathode of the WOLED. The intersection of the anode and cathode decided an active device area of 2×2 mm^2. The EL performance of the WOLED devices were measured by a Photo Research PR-655 spectrophotometer and a Keithley 2400 programmable voltage-current source. The polarized EL performance of the devices were detected using a polarizer in front of the WOLEDs. All of the measurements were operated in air at room temperature.

3 Results and discussion

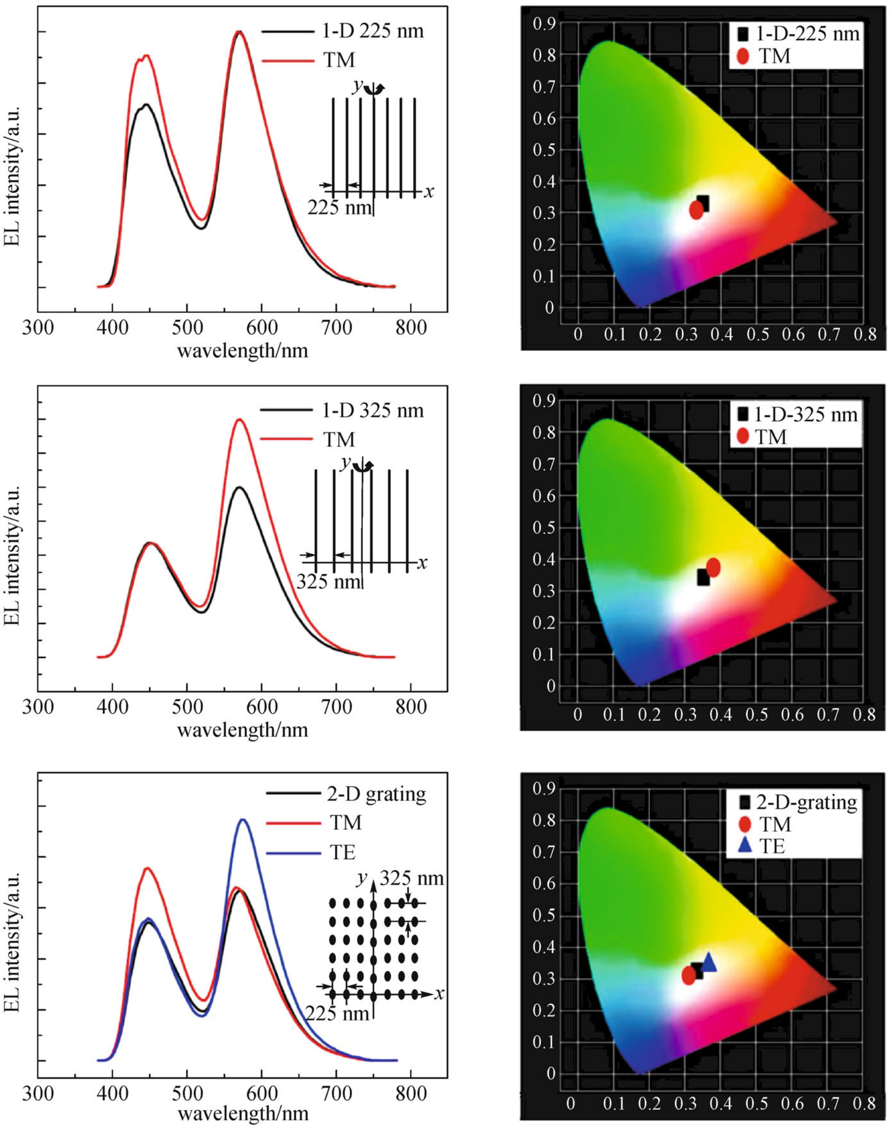
Figure 1(a) shows AFM image of the 2-D dual periodic gratings on the glass substrate fabricated by the holographic lithography technique. There are two sets of corrugations in the dual periodic grating with periods of the 225 and 325 nm, respectively. The intersection angle between the two sets of the microstructure is about 90°. The groove depth was detected to be about 60 nm controlled by tuning the laser fluence. In general, WOLEDs can be obtained by three complementary color strategies (red, green and blue) or two complementary color strategies (orange and blue) in a multi- or a single-layer structure. Here, we chose a simple WOLED structure with two color strategies based on single emitting layer by doping the orange-emitting phosphorescent material $(bzq)_2Ir(dipba)$ into a blue-emitting fluorescent complex $Bepp_2$.

We fabricated WOLEDs with 2-D dual periodic gratings according to the structure shown in Fig. 1(b), and the 1-D mono-periodic microstructured and planar WOLEDs were also prepared for comparison. We measured the linearly polarized EL spectra of the WOLEDs with 1-D or 2-D dual periodic gratings in Fig. 2(a). The Commission International de l′Éclairage (CIE) coordinates were also compared as shown Fig. 2(b). A polarizer is applied in front of the WOLEDs to analyze the polarization of the EL emission. We should note first that the light with the magnetic and electric component vertical with the *xz* plane can be called as transverse magnetic (TM) and transverse electric (TE) polarization, respectively, as shown in the inset of Fig. 2. In the TM polarized EL spectra of 1-D mono-periodic WOLEDs with 225 nm period, the blue emitting peak around 450 nm from $Bepp_2$ is enhanced, and the CIE coordinates is changed from (0.35, 0.33) to (0.33, 0.31)



(a) (b)

Fig. 1 (a) AFM image of the 2-D dual periodic grating with period of 225 and 325 nm; (b) schematic structure of WOLEDs



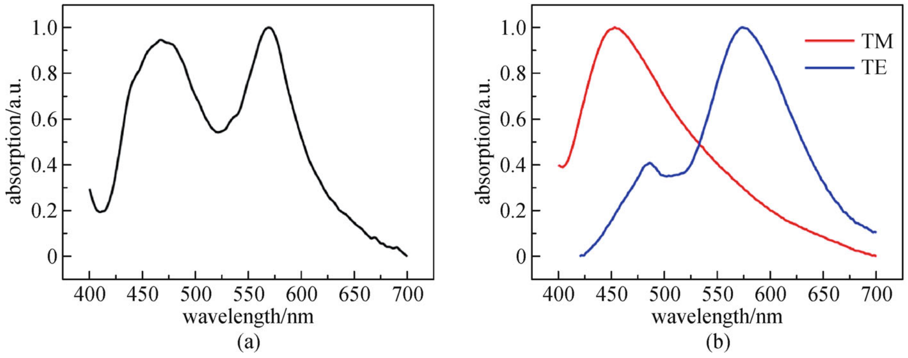
(a) (b)

Fig. 2 Normalized EL spectra (a) and CIE coordinates (b) of the WOLEDs with 1-D 225 nm period, 1-D 325 nm period, and 2-D dual period grating with TM polarization (red), TE polarization (blue), and without polarization (black)

compared with the non-polarized spectra. In the 1-D 325 nm periodic WOLEDs, the 575 nm orange emitting peak from $(bzq)_2Ir(dipba)$ is improved under TM polarization, and the CIE coordinates is changed from (0.36, 0.34) to (0.38, 0.37) accordingly. The 2-D dual periodic microstructured WOLEDs are standard white light emitting devices with the CIE coordinates of (0.33, 0.33), however, exhibit the color tunable property with quite different EL spectra and CIE coordinates under various polarization. In TM polarization, the 2-D dual periodic microstructured devices shows cold-white emission with the CIE coordinates of (0.32, 0.31) and the EL spectrum is enhanced around 450 nm, while the peak of 575 nm is suppressed. Then the emission color can be changed to warm-white by tuning the direction of the polarizer (TE polarization), and the CIE coordinates is changed to be (0.37, 0.35) due to the improved orange emitting peak at 575 nm.

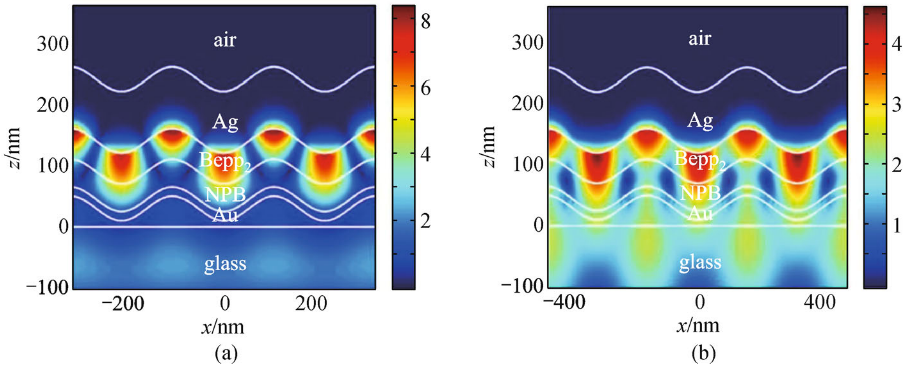
To ascertain the origin of the color tunability associated with polarization in the WOLEDs with 2-D dual periodic gratings, absorption characteristics were measured. Figure 3(a) shows the normalized absorption spectra of the dual peridic microstructured WOLEDs. In the absorption measurement, we chosed a planar WOLED as the reference sample to exclude the intrinsic absorption of the planar metal films and the organic materials at the observed wavelength region, as well as to distinguish clearly the peaks supported by the periodic corrugations. The absorption spectra shows a broadband absorption enhancement with two peaks around 450 and 575 nm, which exhibits an excellent correspondence with the emitting peaks of the WOLEDs. The absorption spectra under TM and TE polarized light source have been further examined as shown in Fig. 2(b). Different from the absorption spectra in Fig. 2(a), only one narrow peak can be found in the polarized spectra located around 450 nm for TM polarization and 575 nm for TE polarization, respectively. To identify the optical modes supported by the dual periodic gratings in the WOLEDs, we calculated the spatial steady-state H_z field intensity distributions as a function of position with the normal incident light across the device structure by using in-house generated finite-difference time-domain (FDTD) codes [14]. Figures 4(a) and 4(b) show the field intensity distributions for the TM polarization with wavelength of 450 nm and TE polarization with wavelength of 575 nm, respectively. The field intensity decays along the direction perpendicular the Ag/organic interface and exhibits its maxima at the Ag/organic interface. The field intensity distributions demonstrate that the absorption peaks at 450 and 575 nm both originate from SPP modes associated with Ag/organic interface, since SPPs are surface wave and propagating along the interface between a metal and a dielectric [15,16]. From above experimental measurements and numerical simulations, we can conclude that the 2-D dual periodic grating with period of 225 and 325 nm can effectively excite SPP modes at 450 and 575 nm according with the emitting peaks of the WOLEDs. SPP mode is one of the main power losses in OLEDs, and the light trapped in the SPP mode can be effective extracted by engaging periodic microstructures [17]. By introducing the 2-D dual periodic grating in the WOLEDs, the trapped emitting light have been extracted around 450 and 575 nm by the two sets of microstructure with period of 225 and 325 nm, respectively. The light excited from SPP modes by the periodic microstructure is confirmed to be polarized [18], as a result, the 2-D dual periodic microstructured WOLEDs exhibit the color tunable characteristics associated with polarization by varying the relative mixing ratio of the orange and blue portions extracted from SPP modes.

The EL performances of the 2-D dual periodic corrugated and planar WOLEDs have been further compared in order to investigate the effect of the dual periodic grating on the devices as shown in Fig. 5. The dual-periodic corrugated WOLEDs show obvious enhancement in both luminance and efficiency. The maximum luminance is increased from 28250 cd/m^2 for the planar device to 40680 cd/m^2 for the dual-periodic device. The maximum current efficiency has been improved from 15.9 to 22.33 cd/A by integrating the dual-periodic grating in WOLEDs, and it reveals a 39.65%



(a)
(b)

Fig. 3 (a) Normalized absorption spectra of the 2-D dual periodic microstructured WOLEDs; (b) normalized TM polarized and TE polarized absorption spectra of the WOLEDs



(a)
(b)

Fig. 4 Simulated distributions of the magnetic field intensity across the 2-D dual periodic corrugated WOLEDs under the 450 nm TM polarizated normal incident light (a) and 575 nm TE polarizated normal incident light (b)

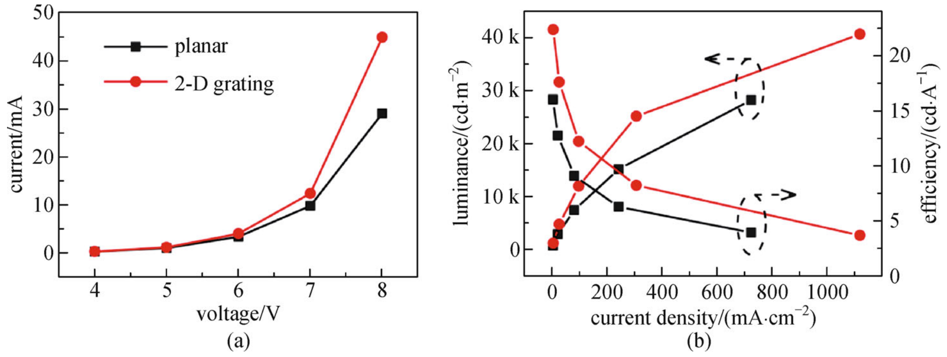


Fig. 5 EL performance of the corrugated and planar WOLEDs. Voltage-current (a) and luminance-current density-efficiency (b) characteristics of the corrugated and planar WOLEDs

enhancement in the current efficiency. The significant improvements in EL performance of the dual periodic corrugated WOLEDs arise from the effective light extraction by excitation and outcoupling of the SPP modes associated with the cahode/organic interface by engaging the 2-D dual periodic gratings [19].

4 Conclusions

In summary, we have introduced the 2-D dual periodic gratings into WOLEDs and color tunable characteristics associated with polarization have been realized. The emitting color of WOLEDs is tuned among standard-white, cold-white and warm-white by tuning the polarization. The experimental and theoretical results demonstrate that the color tunability of the WOLEDs is due to the excitation and coupling of SPP modes by the dual periodic microstructures. The EL performances of WOLEDs have also been improved, and a 39.65% enhancement in current efficiency compared to that of the conventional planar devices has been obtained. The WOLEDs with color tunable characteristics by employing the 2-D dual periodic gratings have the potential commercial applications in both display and lighting.

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