Top-emitting white organic light-emitting devices with down-conversion phosphors: Theory and experiment

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Abstract: White top-emitting organic light-emitting devices (TEOLEDs) with down-conversion phosphors are investigated from theory and experiment. The theoretical simulation was described by combining the microcavity model with the down-conversion model. A White TEOLED by the combination of a blue TEOLED with organic down-conversion phosphor 3-(4-(diphenylamino)phenyl)-1-pheny1prop-2-en-1-one was fabricated to validate the simulated results. It is shown that this approach permits the generation of white light in TEOLEDs. The efficiency of the white TEOLED is twice over the corresponding blue TEOLED. The feasible methods to improve the performance of such white TEOLEDs are discussed.

OCIS codes: (160.4890) Organic materials; (230.3670) Light-emitting diodes.

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1. Introduction

Top-emitting organic light-emitting devices (TEOLEDs) are of interest recently since the light outcoupling from top allows TEOLED onto silicon substrates, higher aperture ratio than the usual bottom-emitting one. White TEOLEDs are particularly suitable for high-resolution active matrix display. However, it remains a challenge to generate white light in TEOLEDs because of the strong microcavity effect in the devices. Thus, extensive efforts have focused on eliminating the microcavity effects in white TEOLEDs.[1, 2] In addition, Kim *et al* reported the white TEOLEDs utilizing microcavity effects.[3] However, the device structure is complex and there is no report on the angular distribution characteristic of the EL spectrum in such device. Furthermore, the structure of present white TEOLEDs comprise different emissive species into the emissive region, thereby, color stability is difficult to be achieved due to different aging of the emissive species. Conventional bottom-emitting white OLEDs with down-conversion phosphors have been demonstrated.[4-8] Currently, Krummacher *et al* reported a high-efficiency (25 lm/W) white OLED based on down-conversion system.[9] The simple device structure, better color stability as the aging rate and high efficiency make them well suited to low-cost lighting applications. However, there is no report on the white TEOLEDs with down-conversion systems. In this paper, the white TEOLEDs based on down-conversion system were investigated from theory and experiment. The results indicated that this approach permits the generation of white light in TEOLEDs.

2. Theory

Firstly, a model combining the microcavity model with the down-conversion model was developed to describe phosphor down conversion in white TEOLEDs. In the model, the white TEOLED comprised a blue TEOLED and the phosphor down-conversion layers capping on top of the cathode of the blue TEOLEDs as shown in Fig. 1. Each phosphor down-conversion layer absorbs a fraction of the input light and emits them at a different wavelength. Besides, the introduction of the phosphor down-conversion layer capping on top of the cathode of the blue TEOLED will change the optical properties of the top cathode and the performances (including EL spectra, efficiency, *etc*) of the blue TEOLED. Thus, the output of the device is given by

$$EL_{out}(\lambda,\theta) = EL_{BT}(\lambda,\theta) + \sum PL_n(\lambda)\cos^z\theta\,,$$

where θ is the viewing angle, $EL_{BT}(\lambda, \theta)$ is the output spectrum of the blue TEOLED with DPPO layer that was calculated using the microcavity theory.[10-12] z value indicates the angular distribution of the phosphor emission and is an adjustable parameter. The commonly observed Lambertian and isotropic distribution corresponds to a value of z=1 and z=0.The phosphor emission $PL_n(\lambda)$ is simulated by the down-conversion model. The photoluminescence emission of the phosphor $P_n(\lambda)$ is normalized so that its integral over all wavelengths is unity. Than, the $PL_n(\lambda)$ is given by[4]

$$PL_n(\lambda) = W_n C_n(\lambda) P_n(\lambda)$$

where W_n is a weight factor and $C_n(\lambda)$ is a self absorption correction, given by

$$W_n = \int Q_n(\lambda) EL0_{BT}(\lambda)\{1-\exp[-\alpha_n(\lambda)l_n]\}d\lambda\,,$$

$$C_n(\lambda) = \frac{\exp[-\alpha_n(\lambda)l_n]}{1-\int Q_n(\lambda)P_n(\lambda)\{1-\exp[-\alpha_n(\lambda)l_n]\}d\lambda}\,,$$

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Where $Q_n(\lambda)$ is the quantum yield of the down-conversion material, $EL0_{BT}(\lambda)$ is the output spectrum of the blue TEOLED without down-conversion layer (i.e. the pump light), $\alpha_n(\lambda)$ and l_n are the absorption coefficient and effective optical path thickness of the nth phosphor layer. The effective optical path thickness is different from the layer thickness of the phosphor layer and is another adjustable parameter.

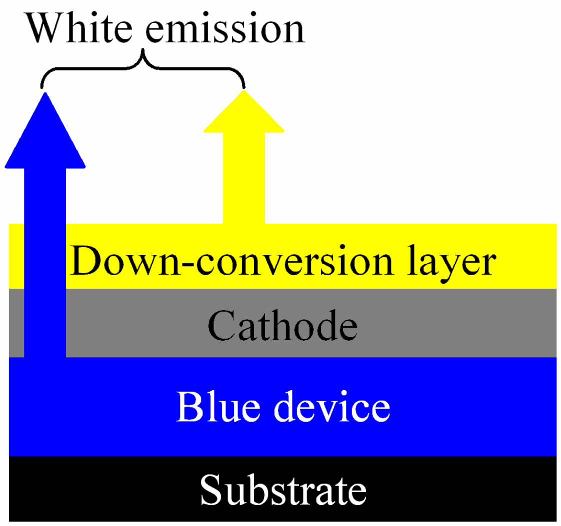

Fig. 1. The schematic device structure of the white TEOLED based on down-conversion system.

3. Experimental details

The devices with a structure of silica coated silicon substrate/Ag (100 nm)/MoO_x (1.0 nm)/4,4',4"-tris(3-methylphenyl-phenylamino)-tripheny-lamine (m-MTDATA, 25 nm)/N,N'-bis-(1-naphthyl)-N,N'diphenyl-1,1-biphenyl-4,4'diamine (NPB, 5 nm)/4,4'-bis(2,2'-diphenylvinyl)-1,1'-biphenyl (DPVBi, 20 nm)/tris-(8-hydroxyquinoline) aluminum (Alq_3, 20 nm)/LiF (1 nm)/Al (1 nm)/Ag (20 nm)/3-(4-(diphenylamino)phenyl)-1-pheny1prop-2-en-1-one (DPPO, 220 nm) were fabricated. In the devices, Ag/MoO_x, m-MTDATA, NPB, DPVBi, Alq_3, LiF/Al/Ag and DPPO[13] were used as anode, hole injection layer, hole transporting layer, blue emitting layer, electron transporting layer, cathode and down-conversion layer, respectively. All films were deposited at pressure below 4×10^{-6} Torr. The deposition rates were controlled by a quartz oscillating thickness monitor and the deposition rates of both organic materials and metal were controlled to about 0.2 nm/s. The characteristics of current-voltage-luminance and EL spectra were measured by a programmable Keithley model 2400 power supply and a Photo-research PR650 spectrometer in air at room temperature. Absorption and photoluminescence spectra of the DPPO film were measured with a Shimadzu a UV-3101PC spectrophotometer and Hitachi F-4500 fluorescence spectrophotometer. Optical constants of the organic materials were measured with variable angle spectroscopic ellipsometry.

3. Results and discussion

Figure 2 shows the absorption, excitation and emission spectra of DPPO. Inset is the optical constants and the chemical structure of DPPO. A yellow emission with the peak wavelength at 548 nm is observed from the PL of DPPO. The absorption spectrum of DPPO measured using spectrophotometer is well agreed with the values derived from k value according to the well-known relationship $\alpha=4\pi k/\lambda$ and the absorption peak is at 420 nm. Besides, there is less superposition between the absorption and emission spectra of DPPO. Thus, the self absorption correction is neglected in our simulation.

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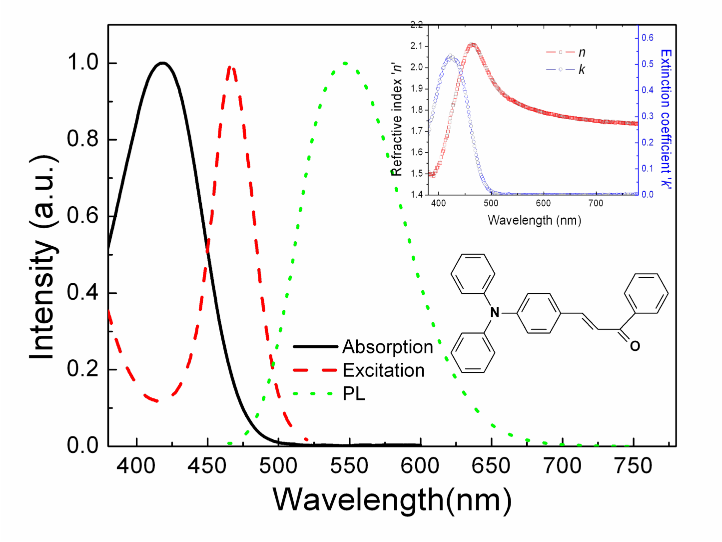

FIG. 2. The absorption, excitation and emission spectra of DPPO. Inset is the optical constants and the chemical structure of DPPO.

Figure 3(a) shows the normalized measured and simulated EL spectra of the TEOLED without DPPO layer (blue TEOLED) at viewing angle of 0° and TEOLED with DPPO layer (white TEOLED) at viewing angle of 0°, 30°, and 60°. We can see that the measured spectra are in excellent agreement with calculated ones, confirming the accuracy of the simulation. The emission peak of the blue TEOLED is 440 nm while the EL spectra of the white TEOLED at different viewing angle show two emission peaks at 472 and 548 nm originating from DPVBi and DPPO, respectively. Besides, the blueshift of the EL peak wavelength with increasing viewing angle which are bound to be present due to the microcavity effect in the TEOLEDs were not observed in the white TEOLED. We attribute it to the filtering effect of the DPPO film. Figure 3 (b) shows the transmission spectra of the Al/Ag/DPPO multilayer film at different incident angles. It can be seen that the transmission is almost the same below 485 nm at different incident angles less than critical angle and the light with the wavelength less than 450 nm almost could not radiated outside the device. As a result, the white device has the same EL peaks at different viewing angle and the redshift of the blue emission in white TEOLED corresponding to the blue TEOLED is observed.

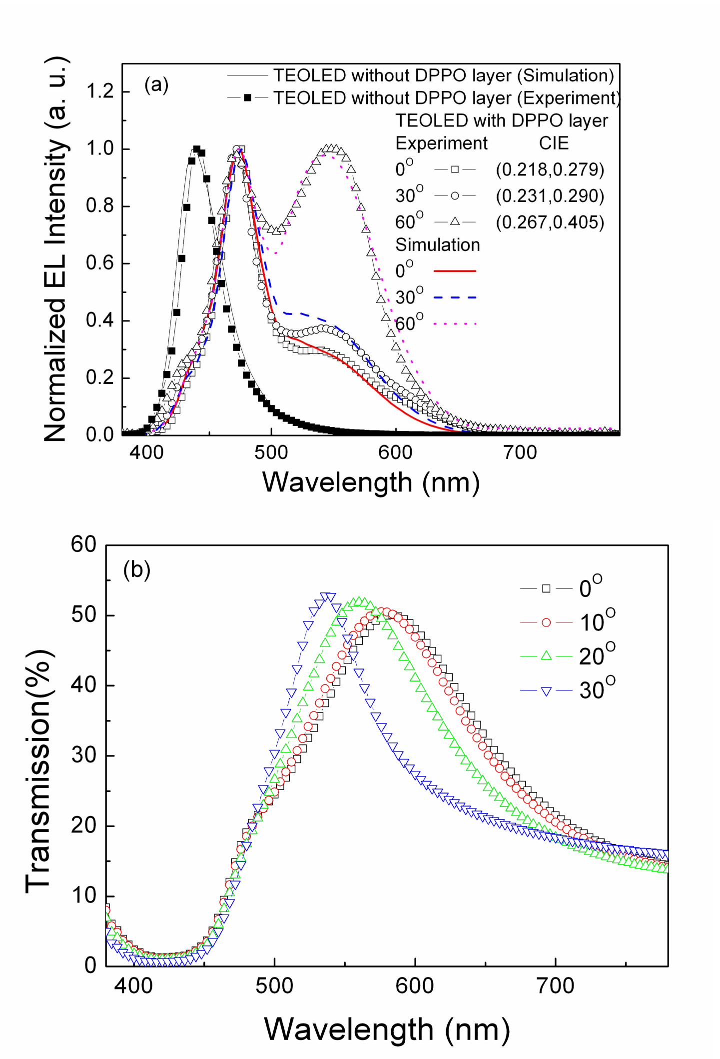

FIG. 3. (a) The normalized measured and simulated EL spectra of the white TEOLED at viewing angle of 0°, 30°, and 60° and (b) the transmission spectra of the Al/Ag/DPPO multilayer film with different incidence angles (incident medium: DPVBi).

From Fig. 3(a), we also can see that the emission intensity of DPPO increases relative to that of DPVBi with the increasing in the viewing angle. The angular dependence characteristic of the emission spectra of the white TEOLEDs can be understood from the following aspects: a more forward directed emission corresponds to a sub-Lambertian distribution was observed in the TEOLED due to the microcavity effects while the emission from DPPO is super-Lambertian distribution (z=0.5). That is to say, the blue emission from DPVBi will decrease more rapidly than the yellow emission from DPPO with the increasing viewing angle. The CIE coordinates of the device are (0.218, 0.279), (0.231, 0.290) and (0.267, 0.405) at viewing angle of 0°, 30°, and 60°, respectively. Besides, the CIE coordinates of the device is voltage independent.

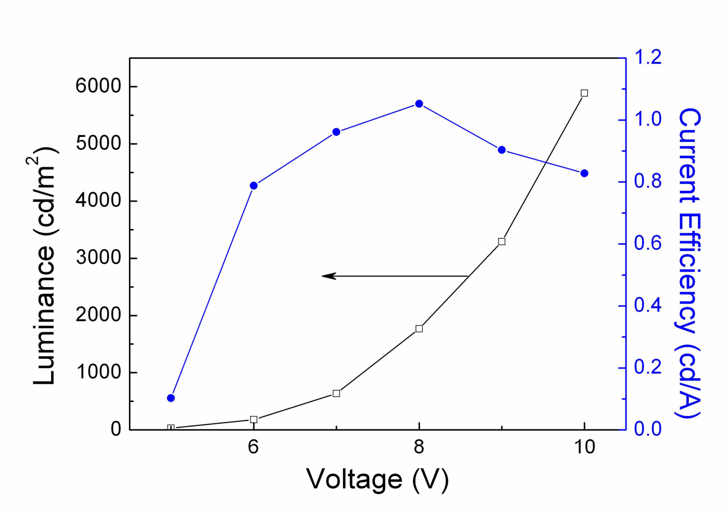

FIG. 4. The voltage-luminance-efficiency characteristics of the device.

Figure 4 shows the voltage-luminance-efficiency characteristics of the device, revealing a luminance of 5887 cd/m^2 at 10 V. The maximum current efficiency of the device can reach 1.1 cd/A which is twice over the corresponding blue TEOLED (0.6 cd/A). The relative low efficiency of the white TEOLED is attributed to the low efficiency of the blue emission material and low quantum yield of the down-conversion material. The performance of the white TEOLED can be improved by using high efficiency down-conversion materials and corresponding blue device.

4. Conclusion

In conclusion, the white top-emitting organic light-emitting device based on down-conversion system was demonstrated theoretically and experimentally. It is shown that this approach permits the generation of white light in TEOLED, the present work will provide a guidance towards the fabrication of the white TEOLED based on down-conversion system.

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