Supporting Information

Manipulation of the size of polystyrene spheres as the templates for internal light out-coupling structures of white organic light-emitting diode

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Enhancement of Red Emission

Top view SEM images of PS spheres with the diameter of 350 nm on the surface of ITO substrates etched for different times are presented in Fig. S1. It is obvious that the diameter of PS spheres gradually decreased as the etching time increased. Fig. S2 presents topographic surface images of corrugated ITO substrates fabricated by etching PS spheres for 90 seconds. From Fig. S2(a), a structure with nano-holes was obtained. The diameter and pitch of the nano-holes is about 170 nm and 350 nm, respectively. The pitch is determined by the size of PS spheres, which is consistent with Fig. S2(d). The corresponding cross-section SEM image is shown in Fig. S2(b). The AFM in Fig. S2(c) shows a relatively clearer image of the corrugated ITO pattern, from which a surface profile was taken along the red line in order to measure the depth of the corrugated structure, as seen in Fig. S2(d). It can be observed that the height of the corrugation was about 45 - 50 nm.

To verify which kind of visible light has been improved based on the corrugated structure with a period of 350 nm, a standard device (reference device) and corrugated devices (with pitch 350 nm and various etching times) were examined. The performance of Alq_3 based OLED devices are presented in Fig. S3. It can be seen that the driving voltage under the same current density in the corrugated device decreased compared with the standard device (Fig. S3(a)). Current efficiency-current density curves and power efficiency-current density are shown in Fig. S3(b) and Fig. S3(c), respectively. Maximum current efficiency of 5.3 cd/A and power efficiency of 4.6 lm/W were achieved when the corrugated ITO glass substrate was fabricated by etching

350 nm PS spheres for 90 seconds. Simultaneously, the maximum current efficiency and power efficiency of the standard planar device was merely 3.5 cd/A and 3.4 lm/W. Therefore, the current efficiency was enhanced by 51.4%. The details are summarized in Table S2. Fig. S3(d) shows the EL spectra of OLED devices based on a planar ITO and a corrugated ITO for PS etched with 90 seconds at 40 mA/cm^2. The red star symbol is the enhancement ratio calculated by the emission intensity of the corrugated OLED device divided by that of the standard OLED device. From Fig. S3(d), the maximum enhancement can reach as large as 2.3-fold at about 620 nm, which means that the corrugated structure fabricated by 350 nm PS spheres etched for 90 seconds is suitable for enhancing the out-coupling efficiency of red light. In addition, the normalized angle resolved EL spectra were also performed. Fig. S4(a) illustrates the staked EL spectra of the corrugated OLED device as the viewing angle varying from 0° to 80°. There are two shoulder peaks which correspond to the out-coupled light shifted with the viewing angle.

Theoretical calculation was also performed by the software of FDTD solution to figure out the origin of the extracted energy of OLED device based on corrugated structure. Fig. S4(c) shows the dispersion diagram in the first Brillouin zone along the crystal orientation of (100). The black stars represent the shift of the emission positions as measured from Fig. S4(a). As we can see, both the waveguide and SPP modes can be extracted from the corrugated OLED devices.

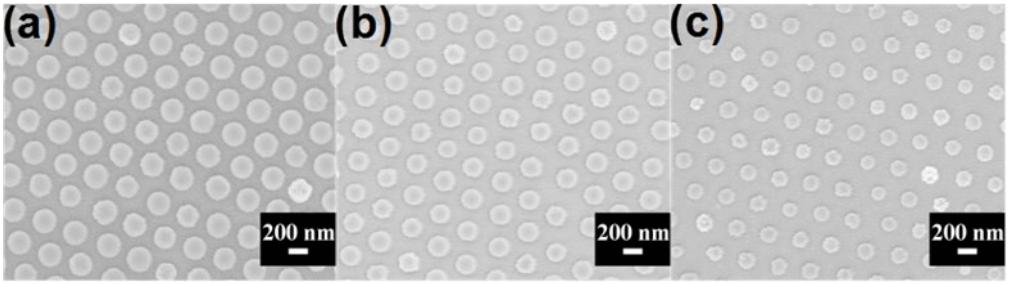

Fig. S1. SEM images of PS spheres (350 nm) after RIE for various times: (a) 75 seconds, (b) 90 seconds, (c) 105 seconds.

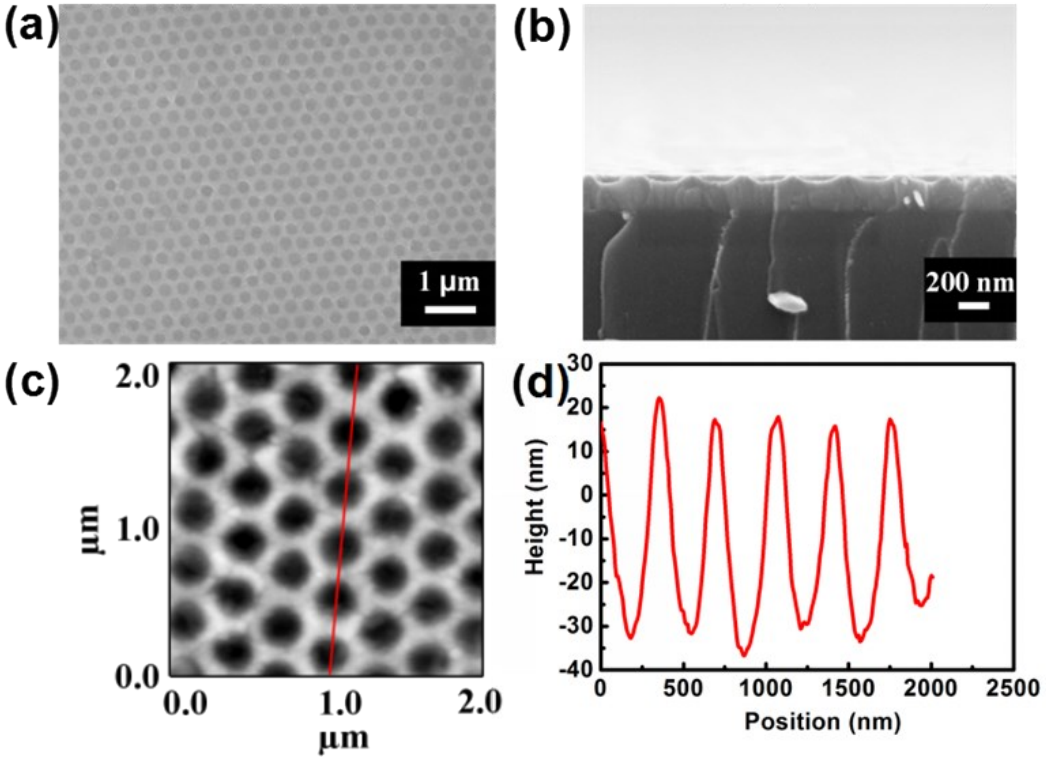

Fig. S2. (a) Top-down, (b) cross-section SEM images and (c) AFM image of the corrugated structure fabricated by etching 350 nm PS spheres for 90 seconds. (d) Surface profile taken along the red line (as defined in Fig. S2(c)).

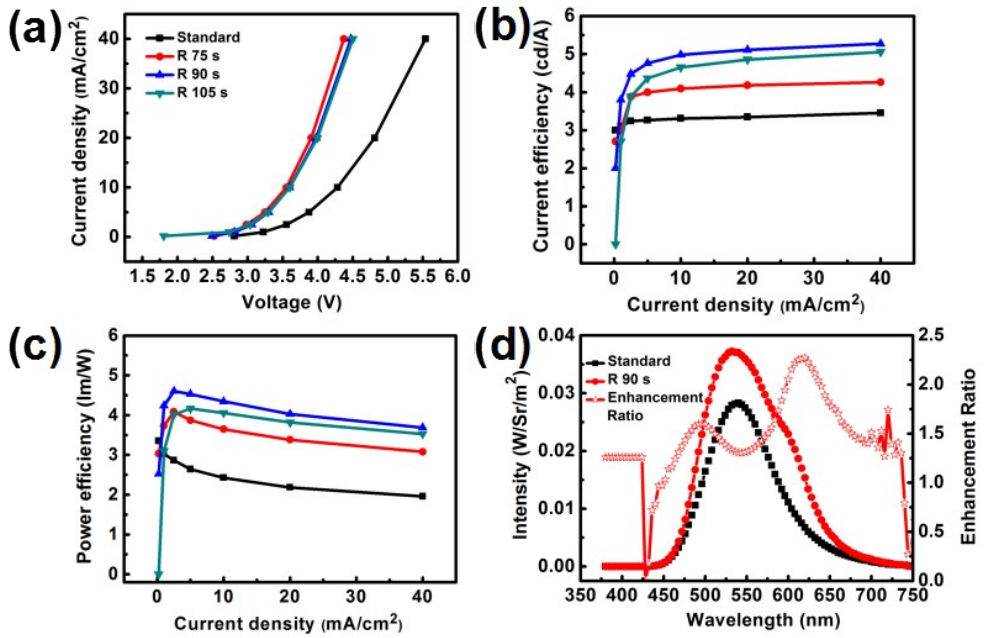

Fig. S3. (a)-(c) The performance of standard and corrugated OLEDs fabricated by 350 nm PS spheres etched for different times based on Alq_3 as the emitter. (d) EL spectra of standard OLED and corrugated OLED fabricated by 350 nm PS spheres etched for 90 seconds at 40 mA/cm^2. The red star symbol is the enhancement ratio calculated by the emission intensity derived from the corrugated OLED divided by that of the standard OLED.

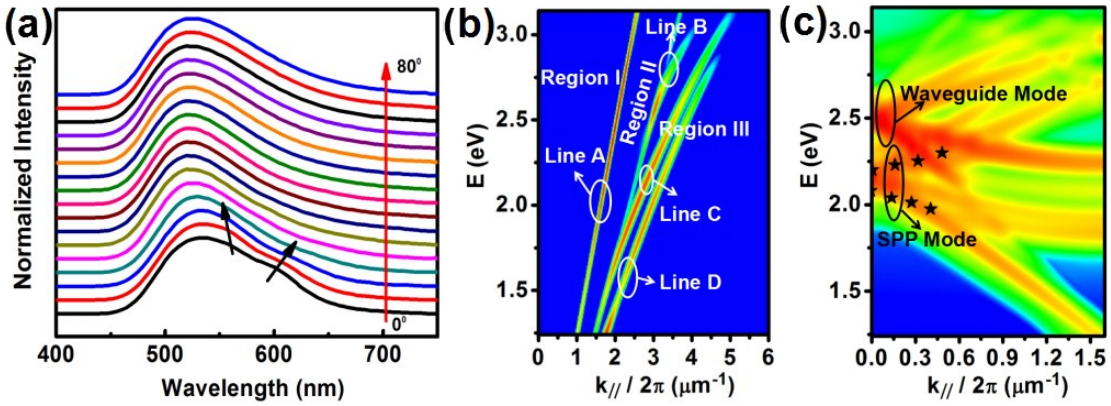

Fig. S4. (a) Stacked EL spectra of OLED devices based on corrugated structure fabricated by etching 350 nm PS spheres for 90 seconds. (b) The simulated dispersion

diagram of the standard OLED device. (c) The simulated dispersion map of corrugated OLED device.

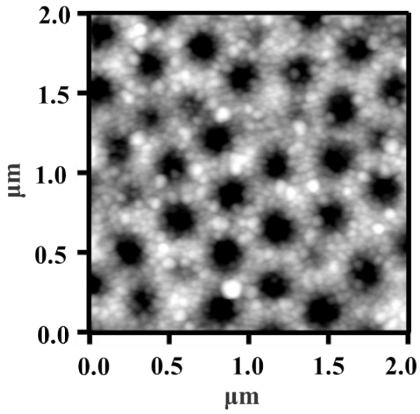

Fig. S5. AFM image of OLED device (W3) based on the corrugated ITO structure fabricated by etching the mixed PS spheres (1:1).

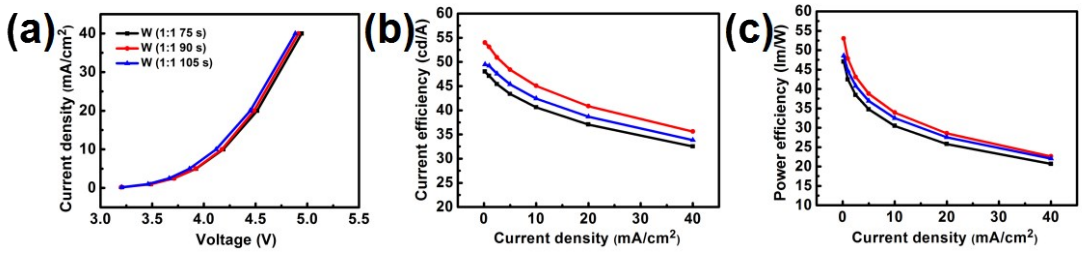

Fig. S6. The performance of white OLED devices based on corrugated structure fabricated by mixed PS spheres (1:1) for various times. (a) Current density-voltage characteristics; (b) Current efficiency-current density curves; (c) Power efficiency-current density curves.

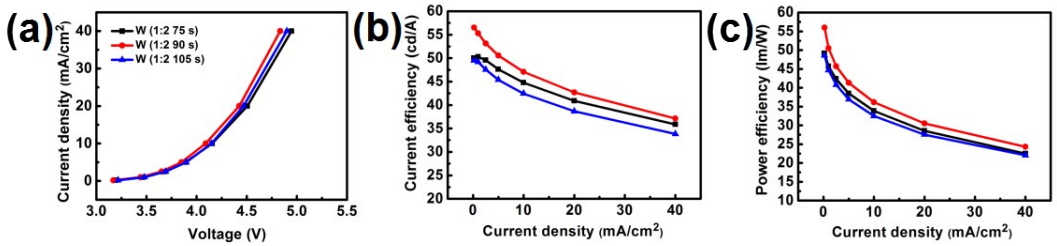

Fig. S7. The performance of white OLED devices based on corrugated structure fabricated by mixed PS spheres (1:2) for various times. (a) Current density - voltage characteristics; (b) Current efficiency-current density curves; (c) Power efficiency-current density curves.

Table S1. Summary of standard and corrugated OLEDs fabricated by 300 nm PS spheres etched for different times based on Alq_3 as the emitter.

Device	Voltage (V)[a]	CE (cd/A)[b]	PE (lm/W)[b]
Standard	3.6	3.5	3.4
G 60 s	2.8	5.7	5.3
G 75 s	3.0	6.2	5.9
G 90 s	3.0	5.6	4.9

a. Voltages at the current density of 2.5 mA/cm^2.

b. Maximum efficiencies of various OLEDs.

OLEDs prepared based on planar ITO and corrugated ITO formed by etching 300 nm PS spheres for 60 seconds, 75 seconds and 90 seconds, and the name of the corresponding devices is labelled as G 60 s, G 75 s and G 90 s, respectively.

Table S2. Summary of standard and corrugated OLEDs fabricated by 350 nm PS spheres etched by different time based on Alq_3 as the emitter.

Device	Voltage (V)[a]	CE (cd/A)[b]	PE (lm/W)[b]
Standard	3.6	3.5	3.4
R 75 s	3.0	4.3	4.1
R 90 s	3.0	5.3	4.6
R 105 s	3.0	5.1	4.2

a. Voltages at the current density of 2.5 mA/cm^2.

b. Maximum efficiencies of various OLEDs.

OLEDs prepared based on planar ITO and corrugated ITO formed by etching 350 nm PS spheres for 75 seconds, 90 seconds and 105 seconds, and the name of the corresponding devices is labelled as Standard, R 75 s, R 90 s and R 105 s, respectively.

Table S3. Summary of WOLEDs based on corrugated structure fabricated by mixed PS spheres (the weight ratio of 300 nm to 350 nm is 1:1).

Device	Voltage (V)[a]	CE (cd/A)[b]	PE (lm/W)[b]
W (1:1 75 s)	3.2	48.0	47.0
W (1:1 90 s)	3.2	54.0	53.0
W (1:1 105 s)	3.2	49.5	48.5

a. Voltages at the current density of 0.2 mA/cm^2.

b. Maximum efficiencies of various OLEDs.

WOLEDs prepared based on planar ITO and corrugated ITO formed by etching mixed PS spheres (1:1) for 75 seconds, 90 seconds and 105 seconds, and the name of the corresponding devices is labelled as W (1:1 75 s), W (1:1 90 s) and W (1:1 105 s), respectively.

Table S4. Summary of WOLEDs based on corrugated structure fabricated by mixed PS spheres (the weight ratio of 300 nm to 350 nm is 1:2).

Device	Voltage (V)[a]	CE (cd/A)[b]	PE (lm/W)[b]
W (1:2 75 s)	3.2	50.3	49.2
W (1:2 90 s)	3.2	56.5	56.0
W (1:2 105 s)	3.2	49.5	48.5

a. Voltages at the current density of 0.2 mA/cm^2.

b. Maximum efficiencies of various WOLEDs.

WOLEDs prepared based on planar ITO and corrugated ITO formed by etching mixed PS spheres (1:2) for 75 seconds, 90 seconds and 105 seconds, and the name of the corresponding devices is labelled as W (1:2 75 s), W (1:2 90 s) and W (1:2 105 s), respectively.