High Efficacy, High Color Quality Hybrid White OLEDs Incorporating Red Quantum Dots with Narrow Emission Bands

Hao Chen*, Juan He*, Jiangshan Chen, Shin-Tson Wu* and Yajie Dong*,**,*****

* College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
** Nanoscience Technology Center, University of Central Florida, Orlando, Florida 32826, USA
*** Department of Materials Science & Engineering, University of Central Florida, Orlando, Florida 32816, USA

Abstract

We propose a hybrid WOLED technology that combines colloidal quantum dot narrow red emitters with organic emitters for high efficacy, high color quality solid state lighting. Spectra analysis indicates this approach will lead to WOLEDs that could achieve high color quality (CRI≥91; R9≥32) at high luminous efficacy of radiation (≥359lm/W).

Keywords: Solid state lighting, organic white light-emitting device, quantum dot, color rendering index, luminous efficacy of radiation

1. Objective and Background

Colloidal quantum dots(CQD) have been intensively investigated as next-generation light sources for display [6] and solid state lighting because of their unique optical properties, including size controlled tunable emission wavelength, narrow emission spectra, high luminescent efficiency and inherent photo physical stability. We recently developed ultra-bright and efficient deep red quantum dot light emitting devices (QLEDs) [7]. The device spectra show FWHM of only 22 nm at CIE coordinates of (0.69, 0.31). More importantly, these devices achieved high peak current efficiency (20.5 Cd/A at ~20, 000 Cd/m2 with a driving voltage of only 3.5 V), high luminous power efficiency (with a peak level of 20.8 Lm/W) and small efficiency roll-off at high driving current density (Figure 1). Ultra-high brightness of 165,000 Cd/m2 can be achieved at current density of 1000 mA/cm2 with a driving voltage as low as 5.8 V which sets a new brightness record for existing organic related red light emitting devices, indicating that double peak brightness of state-of-the art OLED devices can be obtained with only around half of their driving voltages.

Because the thin film QLEDs processes are fully compatible with OLED fabrication, combining this colloidal quantum dot narrow red emitter with existing state-of-the art blue and green organic emitters will be straightforward and are expected to achieve great white spectra that can simultaneously improve CRI and LER. In this paper, we propose a hybrid tandem structured WOLED incorporating the red quantum dot emitters. Spectra analysis by replacing the red emitter in existing WOLED with our red quantum dots indicates that this hybrid approach will lead to a white OLED that could achieve high color quality (Color rendering index: CRI≥91; R9≥32) while maintaining high luminous efficacy of radiation (LER≥359 lm/W), significantly improved from the original OLED which has CRI=82, R9=-15, and LER=341lm/W.

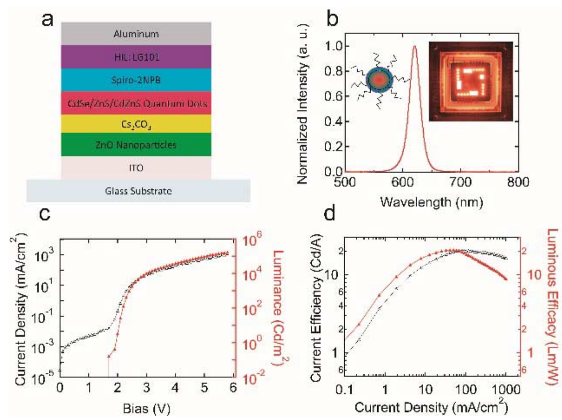

Figure 1. Ultrabright highly efficient, low roll-off inverted quantum-dot light emitting devices (QLEDs) (a) A schematic representation the ultra-bright, high efficiency, inverted QLEDs. (b) Spectra of QLED electroluminescence. (c) Luminance and current density versus driving voltage and (d) Luminous efficacy and current efficiency versus driving current density for typical devices. Adapted from data in reference [7].

2. Hybrid WOLED structure design and fabrication

To realize the WOLED, tandem structure is an adequate solution. Tandem device is a proved strategy for high brightness and long lifetime in state-of-the-art commercial white OLEDs. And the thin film processed red QLED can be easily integrated with existing green and blue OLED in the tandem structure as shown in Figure 2. To fabricate the tandem structured devices, red QLED will be first solution processed. Blue and green organic emitters based OLEDs will be sequentially evaporated on top connecting with charge generation layer (CGL). The interferences between QLED and OLED are minimized and their respective performances are expected to be maintained in the finished white hybrid devices.

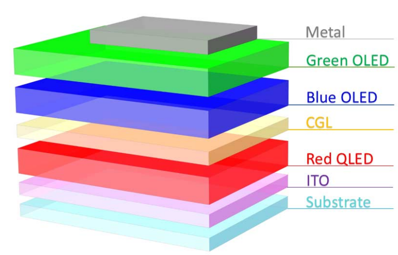

Fig.2 Tandem structure for the red QLED integrated hybrid WOLED

 ISSN 0097-966X/16/4701-0050-$1.00 © 2016 SID

Hybridization of QLED and OLED in tandem structures is expected to be instrumental in realizing the best combination of high stability, high efficacy and high color quality. In addition, the incorporation of solution processed QLED will reduce the thermal-evaporated layer numbers and thus lower the cost of OLED lighting products. Considering the great performance of our red QLED and the broad wavelength tunability for CQD, it's promising to achieve a better white spectra quality with the hybrid combination strategy.

3. Spectra Analysis

1) CRI, R9 and LER

To evaluate the tandem white light sources, an important factor is how well a light source renders the true colors of objects. CRI is the only internationally accepted metric for color rendering evaluation [8].

Procedure for its calculation is to calculate the color differences $\Delta\boldsymbol{E_i}$ of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by the given illuminant. The Special Color Rendering Indices ***Ri*** for each color sample are obtained by

$$\boldsymbol{R_i = 100 - 4.6\Delta E_i} \qquad (\mathbf{i = 1, \ldots, 14}) \qquad (1)$$

This gives the evaluation of color rendering for each particular color. Generally, the Color Rendering Index Ra is given as the average of the first eight color samples

$$\boldsymbol{R_a = \sum_{i=1}^{8} R_i/8} \qquad (2)$$

The score for perfect color rendering is 100. CRI is often used to refer to ***Ra***, when it consists of 15 numbers actually ($\boldsymbol{R_a}$ *and* $\boldsymbol{R_i}(i = 1{:}14)$). The special CRI: R9 should also been considered for the analysis because the red–green contrast is very important for color rendering and red tends to be problematic. Lack of a red component shrinks the reproducible color gamut and makes the illuminated scene look dull [2]. Though R9 is very important, it was not paid high attention before because it's not included in Ra and increasing R9 would heavily reduce luminous efficacy of radiation.

Another important aspect to consider is the luminous efficacy. The energy efficiency of a light source is evaluated by luminous efficacy of a source, which is the ratio of the luminous flux emitted by the source to the input electrical power. It is determined by two factors:

$$\boldsymbol{\eta_V = \eta_e K} \qquad (3)$$

where $\boldsymbol{\eta_e}$ is the radiant efficiency of the source and $\boldsymbol{K}$ is the luminous efficacy of radiation [9], and is determined by the spectral distribution $S(\lambda)$ of the source

$$\boldsymbol{K} = \frac{K_m \int_\lambda V(\lambda)S(\lambda)d\lambda}{\int_\lambda S(\lambda)d\lambda} \qquad \boldsymbol{K_m} = 683\ lm/W \qquad (4)$$

Here $\boldsymbol{K_m}$ is the maximum LER, and its value, 683 lm/W, is defined in the international definition of the candela.

2) High efficiency and high color quality for the red QLED incorporated hybrid WOLED

With the method and algorithm discussed above as white light source evaluation criteria, spectra of one state-of-the-art OLED device [10] have been systematically analyzed in Figure 3 for their potential color and efficacy performance enhancements when being integrated with our ultra-bright red quantum dot emitters with comparison to original white OLEDs [10], current state-of-the-art all organic white OLEDs from LG Chem [11] and all quantum dot white QLEDs [12].

Within the simulation, CRI, R9 and LER [lm/W] are evaluated with spectra obtained by replacing existing red organic emitter peak with QD's narrow red spectra of different incorporation intensity and peak wavelength. LER, CRI and R9 are analyzed separately and all can reach very high value (LER_{peak}=387.5lm/W, CRI_{peak}=91 and $R9_{peak}$=97) exclusively. From the Figure 3, we can clearly get the variation tendency of LER, CRI and R9 along with the peak wavelength and intensity of red QD emitter. Also, by comparing a, b and c, we can see that it's feasible to get a high LER and CRI simultaneously. For R9, however, the high value area mismatches with LER. To increase R9 would heavily reduce LER which can be concluded from Figure.3

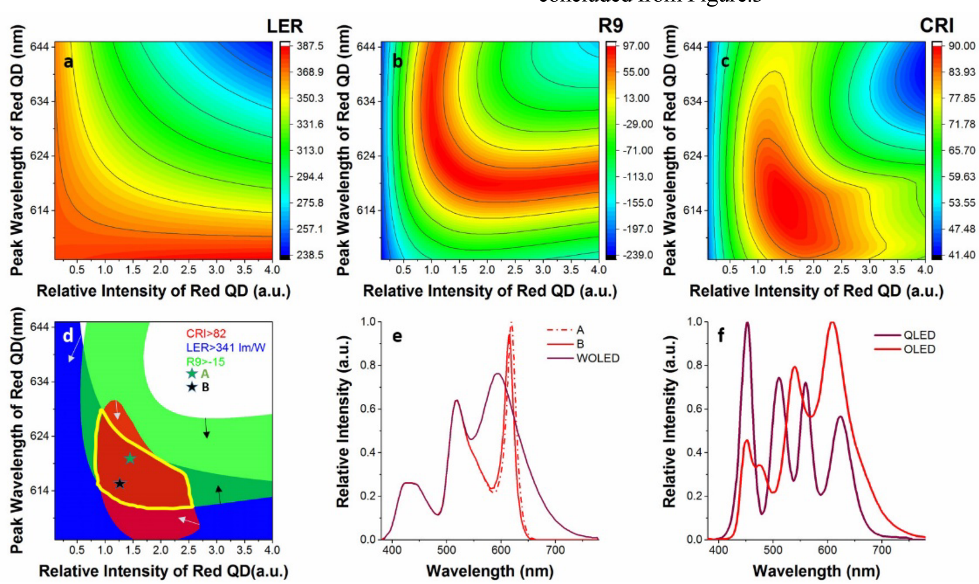

Figure 3. Spectra analysis of the advantages of hybrid white OLED incorporating narrow red QD emitters. Contour plot of (a) LER, (b) R9 and (c) CRI of hybrid white OLED spectra when replacing the red organic emitter peak with red QDs' narrow spectra. (d) Overlap improvement area for wavelength and intensity (surrounded by yellow line) when CRI>82, LER>341lm/W and R9>-15 which are better than all the performance metrics of original WOLED [10]; (e) Spectra of WOLED [10] and two typical spots A and B (as denoted in d) obtained by replacing the red organic emitter peak of WOLED with red QD spectra at different wavelengths and relative intensities. (f) Spectra of state-of-the art all organic emitter WOLED from LG Chem [11] and all QD WOLEDs[12]. Their corresponding performance metrics for spectra in (e) and (f) are listed in table 1

By combining a, b, c in Figure.3, we can get a more trenchant understanding about the three parameters which has been shown in Figure 3.d. In Figure 3 d, contour plot of performance of hybrid WOLED spectra, in which three area of different colors show CRI, R9 and LER better than the identical value of original white OLED, while arrows show the way to increase each metric. Thus, spectra in the overlap area surrounded by yellow line could lead to improvements of all three metrics simultaneously. The overlap area is large enough and can provide us sufficient designing freedom to tune and optimize the three parameters.

Table 1. Performance improvements by replacing existing red organic emitter with Narrow-band red spectra of QDs, as shown in spectra of Figure 3.

	LER[lm/W]	CRI	R9
WOLED	341	82	-15
A	349	90	81
B	359	91	32
All organic WOLED by LG Chem [11]	328	89	31
All QD WOLED [12]	296	93	75

By carefully choosing proper point in the coordinate axis of wavelength and intensity, we can get the preferred red emitter parameter. For the WOLED in [10], an unprecedentedly high R9 value (81) can be expected at LER of 349 lm/W and CRI=90 at the point A, and it can also reach up to LER=359m/W, Ra=91 at point B when choosing a lower R9=32 as listed in table 1, color performance (CRI and R9) and efficacy LER can be improved simultaneously which shows the great advantage over original WOLEDs. Also, Case A can achieve ~18% improvement in LER with comparable color performance to state-of-the art all quantum dot White LED [12], while case B can get ~9.5% improvement in LER with much better color than state-of-the art all organic white OLED from LG Chem [11].

These analysis results show that narrow red QD emitter can effectively improve both color rendering and optical efficiency over state-of-the art white OLEDs and the ability to tune peak wavelength and relative intensity of red quantum dot emitter also offer the hybrid white OLED system flexibility to target special color or efficiency with the same organic emitter materials. So as long as their respective emission properties can be well reserved in the hybrid system, integrating red QDs into white OLED emitters will bring breakthroughs to efficiency and color performances of OLED based solid state lighting.

4. Impact

We propose a hybrid tandem structured white OLED technology that combines our recently developed colloidal quantum dot narrow red emitters with existing blue and green organic emitters for high efficacy, and high color quality solid state lighting. The rationale behind device structure design has been discussed with detailed fabrication process plan. Spectra analysis indicates that optimization of this hybrid approach will lead to white OLEDs that could achieve high color quality (Color rendering index: CRI≥91; R9≥32) while maintaining high luminous efficacy of radiation (LER≥359 lm/W). The proposed hybrid white OLED will be instrumental for highly competitive white lighting source.

5. References

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