Doubling the Light Outcoupling Efficiency of Quantum Dot Light Emitting Diodes

*Ruidong Zhu, Zhenyue Luo, and Shin-Tson Wu**
***College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816**

Abstract
We utilize the dipole model to analyze the light outcoupling and angular radiation pattern of the quantum dot light emitting diodes (QLEDs). Red, green and blue QLEDs are used as examples and the simulation results match well with the experiment. We then confirm that by combining a high refractive index glass substrate with macroextractors, the light outcoupling efficiency can be doubled. And electroluminescent spectra analysis at different angle demonstrates that all three QLEDs have small color shift.

Author Keywords
Quantum dot LEDs; light outcoupling; color shift.

1. Objective and Background

Quantum dot (QD) is a strong candidate for the next generation display because of its narrow emission spectrum and pure, saturated color [1-2]. While the photoluminescence (PL) QDs have already been employed in commercial liquid crystal displays [3-4]; the electroluminescent (EL) type, namely Quantum dot light emitting diodes (QLEDs) are still under development to improve their external quantum efficiency (EQE) and lifetime. The EQE of a QLED is governed by the outcoupling efficiency η, the effective quantum efficiency q_{eff}, and the charge balance γ as [1]:

$$EQE = \eta IQE = \eta \gamma q_{eff} \tag{1}$$

Here IQE is the internal quantum efficiency of the QLED. And the effective quantum efficiency q_{eff} can be determined from the intrinsic quantum efficiency q by the following equation [1]:

$$\frac{q_{eff}}{q} = \frac{k_r^*}{k_r^* + k_{nr}} = \frac{Fk_r}{Fk_r + k_{nr}} = \frac{F}{qF + 1 - q} \tag{2}$$

Here k_r, k_{nr}, and k_r^* are the exciton radiative recombination rate, the exciton non-radiative recombination rate and the modified exciton radiative recombination rate, respectively. F is the Purcell factor which describes how the QLED cavity modifies the exciton recombination rate from k_r to k_r^*. In this paper the authors utilize the dipole model to analyze the outcoupling efficiency of the QLED, which will greatly influence the EQE of the QLED. A red QLED taken from [5] is used as an example and the simulation results match well with the experimental results. The model is also extended to green [6] and blue [7] QLEDs. The outcoupling efficiency can be doubled by using high refractive index glass and macroextractors. The emission spectra and the color shift of the QLEDs are also studied.

2. Structure of the QLEDs and the dipole model

Besides the glass substrate (BK7 glass) used in all these three QLEDs, the red QLED consists of layers of ITO (40 nm)/ZnO nanoparticles (45 nm)/CdSe-CdS core-shell QDs (45 nm)/NPB (65nm)/HAT-CN (15 nm)/Al (100 nm). This QLED device has already been proved to be highly efficient [5]. The Green QLED consists of layers of ITO (40 nm)/PEDOT: PSS (40 nm)/poly-TPD (45 nm)/CdSe-ZnS core-shell QDs (13-25nm)/ZnO nanoparticles (35 nm)/Al (100 nm). And the Blue QLED is with layers of ITO (40 nm)/PEDOT: PSS (30 nm)/TFB (40 nm)/ZnCdS-ZnS graded core-shell QDs (45 nm)/ZnO nanoparticles (30 nm)/Al (100 nm). The PL spectra of the three QLEDs are taken from [5-7].

In [1], the authors utilize the rigorous dipole model to calculate the power dissipation spectra of the three QLEDs. In this model, the QDs are treated as isotropic electric dipole oscillators inside a multilayer medium. In this model, the multilayer structure is first simplified to a three-layer structure by the transfer matrix approach to calculate the Fresnel coefficients of both top contact and bottom contact. And then the power generated by dipoles within a three-layer structure normalized to the power emitted in an infinite medium is given by

$$P = 1 - q + qF = 1 - q + q\int_0^\infty K(k_x)dk_x \tag{3}$$

K is the power dissipation density per unit dk_x, and k_x is the in-plane wave vector for waves propagating in the emitting medium. Both K and k_x can be determined by the wavelength and emitting angle dependent Fresnel coefficients. A more detailed explanation of the dipole model can be found in [1].

3. Light outcoupling of the QLEDs

With the dipole model, we can understand the power dissipation of the QLEDs. Fig. 1 illustrates the power dissipation of the red QLED if we assume q_{eff} =1 and γ=1. The power dissipation spectra can be divided into five parts: 1) Direct Emission: this part indicates how much of the emitted light can be outcoupled and travel in the air; 2) Substrate mode: in this mode the light experience total internal reflection at the glass/air interface; 3) Waveguide mode, in this mode light is guided inside the organic layers because of the TIR at the interface of the ITO and glass interface; 4) Surface Plasmons: this mode corresponds to the evanescent wave at the QD/metal interface and 5) Optical Absorption: as the absorption coefficients of the organic layers are non-zero, some of the emitted light is absorbed inside the QLED cavity and can be attributed to optical absorption. If the electrical loss is negligible, the direct emission part is equivalent to the EQE. Here the direct emission part account for 19.2% of the total radiated power, which matches well with the experimental results.

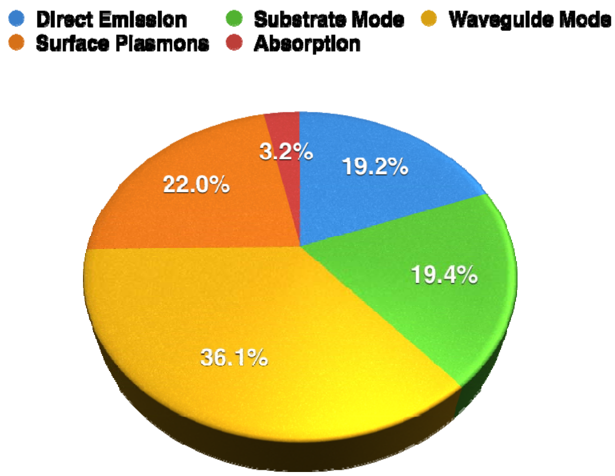

Figure 1. Power dissipation spectra of the red QLED.

The charge balance of contemporary green and blue QLEDs are not as good as the red QLEDs, and thus the exact number of the power dissipation spectra isn't of much help for their designs. However, compared with the experimental results, our model shows the same trend for the green QLEDs. As is shown in Table 1, when we decrease the QD layer thickness from 25 nm to 13 nm, the outcoupling efficiency decreases monotonously, which matches the trend of the experiment in [6]. And if we assume an IQE of 10.04%, we can achieve an EQE of 1.35% at the QD layer thickness of 25nm, which is the same as the experimental results.

Table 1. Comparison of the outcoupling efficiency of the green QLEDs with different QD layer thickness

QD Layer thickness(nm)	Outcoupling efficiency
25	13.4%
19	13.0%
16	12.8%
13	12.5%

For the newly proposed high efficiency blue QLED, if we assume a quantum yield of 90% (q=0.9) [7] and perfect charge balance (γ=1), the EQE of the blue QLED is 10.5%, which matches well with the experimental results.

If we take a look at the outcoupling efficiencies of the RGB QLEDs, none of them reaches more than ~30%, and this so-called ceiling effect is caused by the total internal reflection (TIR) at the glass/air interface. The maximum outcoupling efficiency can be estimated as $0.5n^{-2}$, where n is the refractive index of the glass substrate. There are a few approaches to improve light outcoupling, and the most straightforward approach is to use macroextractors combined with high refractive index glasses to circumvent TIR. With this approach, both the direct emission part and the substrate mode can be outcoupled. Fig. 2 shows how the refractive index of the glass substrate influence the outcoupling of the red QLED. As the macroextractors can extract both the direct emission part and the substrate mode, we can see that if we increase the refractive index of the substrate, we can outcouple more light from the QLED, for example, if we use macroextractors and a glass substrate with a refractive index of 2.0, we can extract ~80% of the total dissipated power. Which is 2X enhancement compared with the regular BK7 glass (n=1.5). However, if we keep on increasing the refractive index of the glass substrate, the light outcoupling efficiency saturates, which can be attributed to the intrinsic optical absorption inside the QLED. In this sense, the optimal refractive index of the glass substrate is 2.0. Such conclusions can also be extrapolated to green and blue QLEDs.

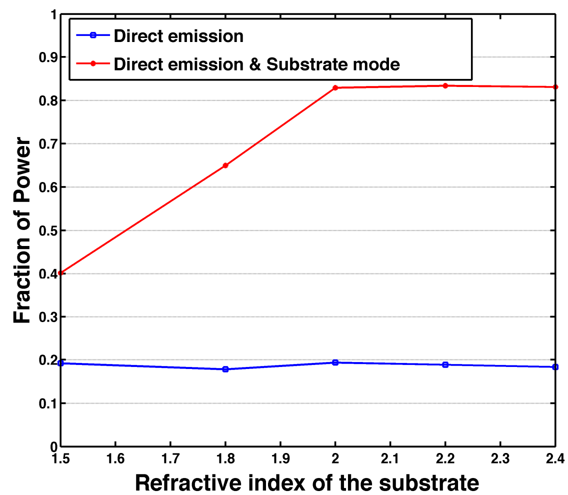

Figure 2. How the refractive index of the substrate influence the light outcoupling of the red QLED

4. Spectra and color shift analysis of the QLEDs

Besides the light outcoupling efficiency, the EL spectra of the RGB QLEDs are also calculated, Fig. 3 depicts the EL spectra of the red QLED under different viewing angle, it is obvious that the emission spectrum is narrow and symmetric even at large angle, which indicates small color shift.

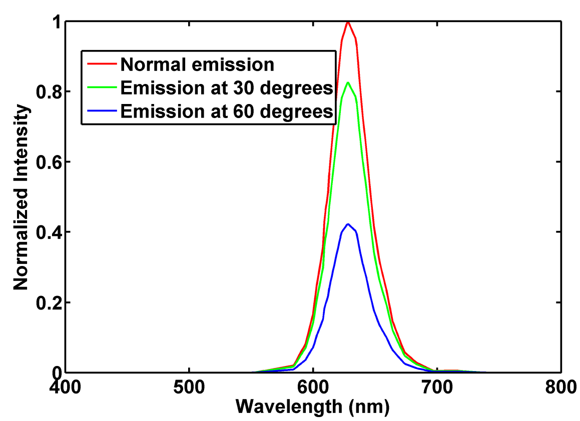

Figure 3. Emission spectra of the red QLED under different angles

The color shift calculation of the RGB QLEDs also proves this, as shown in Fig. 4. From Fig. 4 it is observable that the color shift of all the three QLEDs are less than 0.002 even at the viewing angle of 80°. This means that for future QLEDs display, the display can have almost the same color gamut at extremely large viewing angle.

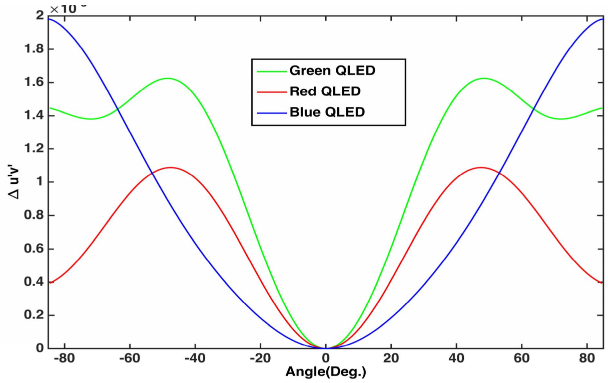

Figure 4. Color shift of the RGB QLEDs

To demonstrate the idea of RGB QLED display, we use the three QLEDs listed above and analyze the color gamut they form. If we set the reference white of the display to be D65, the spectra of the display system should be like Fig. 5 (a), and the color gamut of the display is shown in Fig. 5 (b). As the central wavelength of the RGB QLEDs are not set to that of the Rec. 2020 [8] standards, the color gamut covers only 76% of the Rec. 2020 standards. However, our analysis, which is not drawn here indicate that even at the angle of 60°, the QD display still covers 75.9% of the Rec. 2020 standards. This implies that if we further shift the central wavelength of the QLEDs, we can make a display that matches the Rec 2020 standards better, and do not have the problem of color gamut shrink at large viewing angle.

Here we should mention that small color shift for the RGB color separately does not necessarily mean a small color shift for the reference white. This is because the angular light intensity distribution might be different for different color, thus tuning the intensity of the RGB QLEDs is still required for large viewing angle.

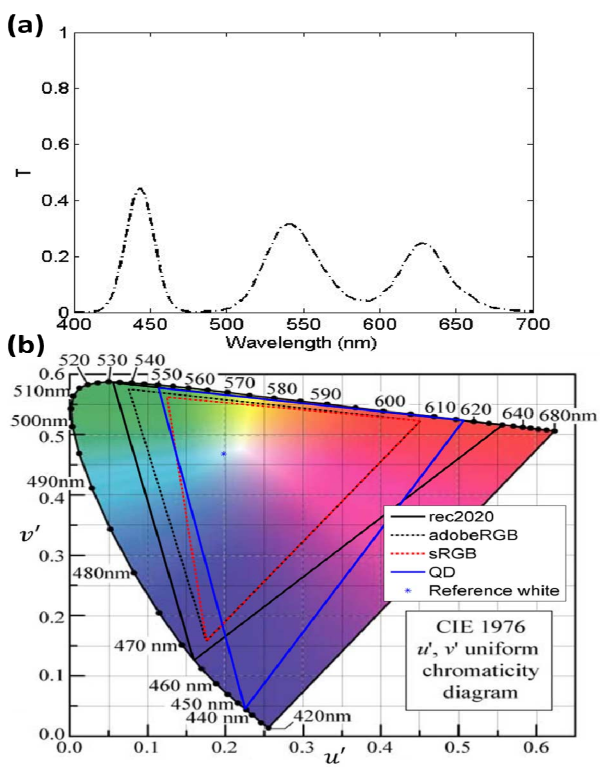

Figure 5. (a) Emission spectra of the RGB QLED display and (b) the color gamut of the RGB QLED display.

5. Conclusion

We have analyzed the outcoupling efficiency of QLEDs using the dipole model. The results match well with experimental data and clearly illustrate the ceiling effect in light outcoupling. And then it is demonstrated that utilizing high refractive index glass and macroextractors can double the light outcoupling efficiency. The emission spectra and color shift of the QLEDs are also analyzed.

6. Acknowledgments

The authors are thankful to Prof. Jin Jang from Kyung Hee University for helpful information and thoughtful discussion, Dr. Bert Scholz from Universität Augsburg for helping us with the dipole model, and Dr. Qi Hong and Prof. Yajie Dong of University of Central Florida for the insightful discussion.

7. References

[1] R. Zhu, Z. Luo and S.-T. Wu, “Light extraction analysis and improvement in a quantum dot light emitting diode,” Optics Express **22**(S7), A1783-A1798 (2014).

[2] A. Castan, H.-M. Kim, and J. Jang, “All-Solution-Processed Inverted Quantum-Dot Light-Emitting Diodes,” ACS Applied Material and Interfaces **6**(4), 2508–2515 (2014).

[3] Z. Luo, D. Xu, and S.-T. Wu, “Emerging Quantum-Dots-Enhanced LCDs,” Journal of Display Technology **10**(7), 526–539 (2014).

[4] Z. Luo, Y. Chen, and S.-T. Wu, “Wide color gamut LCD with a quantum dot backlight,” Optics Express **21**(22), 26269–26284 (2013).

[5] B. S. Mashford, M. Stevenson, Z. Popovic, C. Hamilton, Z. Zhou, C. Breen, J. Steckel, V. Bulovic, M. Bawendi, S. Coe-Sullivan, and P. T. Kazlas, “High-efficiency quantum-dot light-emitting devices with enhanced charge injection,” Nature Photonics **7**(5), 407–412 (2013).

[6] L. Qian, Y. Zheng, J. Xue, and P. H. Holloway,” Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures” Nature Photonics **5**(9), 543–548 (2011).

[7] H. Shen, W. Cao, N. T. Shewmon, C. Yang, L. S. Li, and J. Xue, “High-Efficiency, Low Turn-on Voltage Blue-Violet Quantum-Dot-Based Light-Emitting Diodes,” Nano Letter **15**(2), 1211-1216 (2015).