Enhancing the Light Outcoupling Efficiency of Quantum-Dot Light Emitting Diodes with Periodic Microstructures

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Abstract

We propose a periodic SiNx/SiO2 microstructure to effectively extract light from quantum-dot light emitting diodes (QLEDs). The FDTD simulation results show that direct emitting efficiency can be doubled while keeping an indistinguishable color shift. This approach can also be applied to optimize the performances of green and blue QLEDs.

Author Keywords

Quantum dot light emitting diode, light outcoupling, color shift.

1. Introduction

Colloidal quantum dots (QDs) exhibit several attractive features: high photoluminescence quantum efficiency, tunability of emission peak wavelength through particle size control, and narrow emission bandwidths which are able to provide pure, saturated color [1, 2]. These excellent features make QDs attractive for liquid crystal displays (LCDs) as backlight [3, 4] and organic light-emitting diodes (OLEDs) [5] to provide reliable and saturated red, green, blue (RGB) primaries, which forms a large color gamut for next generation display.

Photoluminescence (PL) and electroluminescence (EL) are two types of QD operation mechanisms. PL QDs have been integrated into LCD backlight to provide vivid colors with ~15% increased optical efficiency [4]. By dispersing red and green QDs in a plastic film and tuning the size of QDs to create right wavelengths, quantum dots enhancement films (QDEFs) have been manufactured [6]. The red/green QDs are excited by the blue LED to emit pure red and green lights. Several companies including Nanosys, QD Vision, 3M, and Nanoco/Dow are actively engaging into this area. It is reported that 115% color gamut in CIE1931 and 140% in CIE1976 color space can be achieved with optimized QDEFs [3]. The first commercial applications were found in Sony's Triluminos LCD TVs and Amazon Kindle Fire tablets. In 2015, both LG and Samsung rolled out QD LCD TVs.

Meanwhile, EL QDs, namely quantum dot light-emitting diodes (QLEDs) [7] remain inferior to OLEDs in terms of brightness and efficiency. Replacing the organic emitting layer with QDs, QLEDs are able to provide Gaussian-like emission spectra with a full width half maximum (FWHM) below 30nm [5], which shows more saturated colors than typical OLEDs (FWHM ~100nm) [8]. However, the light output is fairly influenced by the external quantum efficiency (EQE). The outcoupling efficiency is constrained by the ~20% ceiling of the total radiated power [9-11]. Therefore, enhancing light extraction of QLED structures plays an important role in the application for QLEDs. Recent result shows that by combining a high refractive index substrate with macroextractors, the light outcoupling efficiency can be doubled [12]. This method is realistic for QLED for the purpose of illumination. But for displays, the pixel size is in the order of ~100μm (TVs and monitors) to ~50μm (cell phones). It is not feasible to assemble macroextractors onto these small pixels. It is reported that the outcoupling efficiency can be enhanced by integrating periodic microstructures into OLEDs [13-15]. This approach opens up a window to improve the optical performance of OLEDs for display.

In this paper, we use the dipole model to analyze the amount of power coupled to different optical channels for a typical red QLED [12]. By embedding periodic microstructure between cathode and glass substrate, our FDTD simulation results indicate that we can double the light outcoupling efficiency, while keeping narrow emission spectra and indistinguishable color shift. This approach can also be applied to optimize the performances of green and blue QLEDs.

2. Red QLED and its outcoupling efficiency

In our analysis, the red QLED consists of layers of glass substrate BK7 (3000nm)/ ITO (indium-tin-oxide) cathode (40nm)/ ZnO (zinc oxide nanoparticles) electron-transporting layer (45nm)/ CdSe-CdS (cadmium selenide-cadmium sulfide) core-shell quantum dots layer (45nm)/ NPB hole transporting layer (65nm)/ HAT-CN hole injection layer (15nm)/ Aluminum anode (100nm). Figure 1 (a) depicts the structure of the proposed red QLED and Fig. 2(b) shows the PL spectra of the red QLED. Its FWHM is about 30nm and the central wavelength is 615nm [5].

Generally, the QDs can be treated as isotropic electric dipole oscillators in the emitting layer. This dipole model is built to provide the power dissipation spectra of a QLED. In this model, the multilayer structure is simplified to a three-layer structure by the transfer matrix approach and the quantum dots are described as isotropic emitters. The external quantum efficiency (EQE) of QLEDs can be expressed as:

$$EQE = \eta IQE = \eta \gamma q_{eff} \quad (1)$$

where η is the outcoupling efficiency and IQE is the internal quantum efficiency. The IQE is tightly related to the effective quantum yield q_{eff} which is close to the quantum yield q of the quantum dots and the charge carrier balance γ (γ=1 at the steady state). The power generated by dipoles within a three-layer

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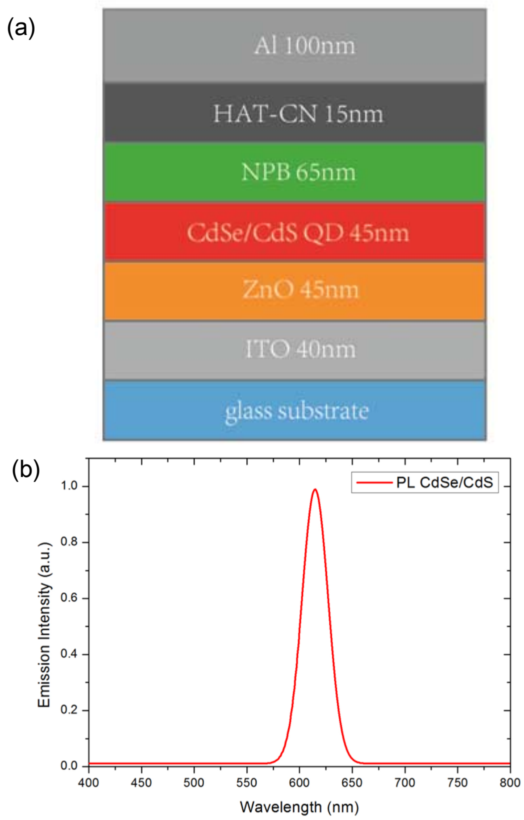

Figure 1. (a) A typical structure of red QLED and (b) the PL spectra of the red QD reported in Ref. [5].

structure normalized to the power emitted in an infinite medium is given by [9]:

$$P = 1 - q + qF = 1 - q + q\int_{\lambda_1}^{\lambda_2} S(\lambda)\int_0^{\infty} K(k_x)\,dk_x\,d\lambda \tag{2}$$

where $K(k_x)$ is the power dissipation density regarding the in-plane wave vector k_x for waves propagating in the emitting layer.

The power dissipation spectrum can be split into four modes: direct emission, substrate mode, waveguide mode, and surface plasmons. Each mode can be sorted out by the in-plane wave vector k_x: 1) Direct emission: $0<kx\leq k_0 \cdot n_{air}$. It denotes the amount of light which can leave the QLEDs; 2) Substrate mode: $k_0 \cdot n_{air}<kx \leq k_0 \cdot n_{glass}$, which denotes the amount of light trapped in the glass substrate due to total internal reflection (TIR); 3) Waveguide mode: $k_0 \cdot n_{glass}<kx\leq k_0 \cdot n_{eff}$. The radiation of dipoles in this mode does not enter the glass substrate and it is guided in the layers between glass substrate and cathode, where n_{eff} is the equivalent refractive index of ITO, QDs, and organic layers; 4) Surface plasmons: $k_0 \cdot n_{eff}<k_x$. It denotes the evanescent wave at the organic-ITO interface.

Among all the approaches, the most straightforward and economic way to enhance light outcoupling is to optimize the QLED stack by varying the layer thickness. For example, Fig. 2 shows the contributions of different optical channels as a function of NPB (HTL) layer thickness for the QLED structure. It is obvious that as the NPB layer is between the Al anode and the emitting layer, the variation of NPB layer thickness greatly modifies the QLED cavity, as can be seen from the oscillation of the direct emission part. And it is obvious that the coupling to the surface plasmons is mainly determined by the distance from the emitting layer to the metallic electrode. Thus, increasing the NPB layer thickness greatly reduces the surface plasmons mode. However, the reduced surface plasmons mode mainly transfers to the waveguide mode; the direct emission mode and the substrate mode are still governed by the EQE ceiling. At 75nm, the direct emission reaches the maximum value of 19%. Figure 3 shows the amount of power coupled to different optical channels for the proposed red QLED.

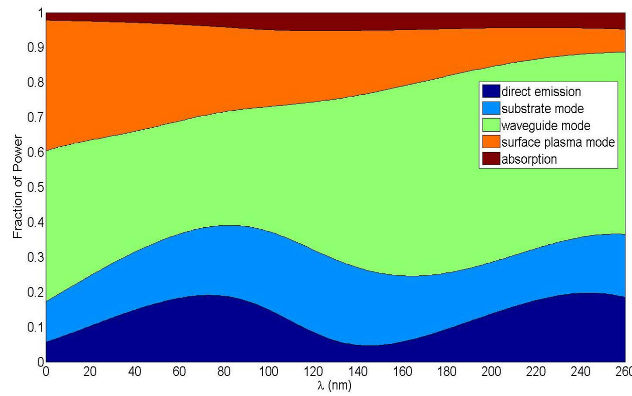

Figure 2. Changing the proportions of different channels by tuning the thickness of NPB layer for QLED structure.

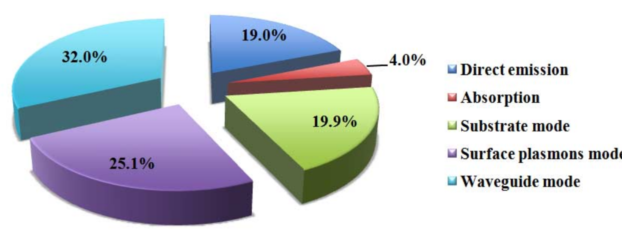

Figure 3. Amount of power coupled to different optical channels for the proposed red QLED.

3. Outcoupling efficiency of QLED with periodic microstructure

From Fig. 3, a large amount of power dissipates inside the QLED because of TIR. Both surface plasmons and waveguide mode power account for the largest proportion. Therefore, extracting the waveguide mode power from a QLED can effectively enhance the EQE of the QLED. While the TIR of substrate mode occurs at the glass/air interface, the TIR of waveguide mode appears at the interface of glass and the electrode (ITO in this case). To extract the light from waveguide mode, a periodic microstructure is embedded in between the glass substrate and the ITO layer [13, 14, 15]. Fig. 4 shows the new QLED structure. The following processes are implemented: 1) SiN_x nano-rods with ~100nm height and ~600nm diameter are formed on the glass substrate; 2) a SiO_2 nano-film is deposited onto the SiN_x nano-rods with an over-coated height of ~200nm; 3) a SiN_x nano-film with ~20nm height is then deposited onto the SiN_x/SiO_2 nano-film to suppress the TIR between ITO and SiO_2.

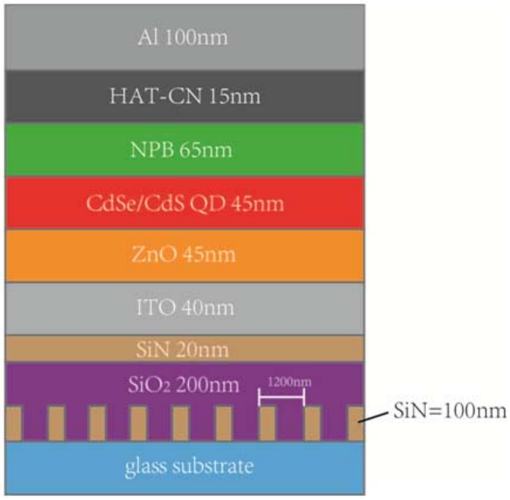

Figure 4. Red QLED with SiN_x/SiO_2 periodic structures.

Next, we used the Finite-Difference Time-Domain (FDTD) method to analyze the light extraction efficiency. Results are plotted in Fig. 5. For a planar QLED structure, the angular emission pattern keeps rather close to the Lambertian light shape at the central wavelength, which is consistent to most of the experimental angular emission patterns of reported LEDs. While for the proposed QLED with a periodic microstructure, the peak emission intensity is more than 2.2X larger than that of the equivalent conventional QLED at on-axial direction. By considering the total direct emitting power in both cases, a doubled enhancement is achieved, indicating that nearly 40% of the dissipated power can be extracted from the QLED in the form of direct emission. Fig. 6 shows the luminance distribution for the purpose of display research. Such conclusion can also be extrapolated to green and blue QLEDs.

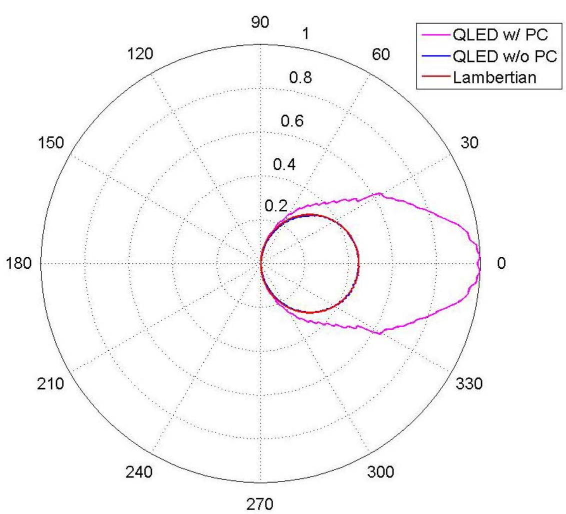

Figure 5. Angular emission patterns of the red QLED with and without microstructures.

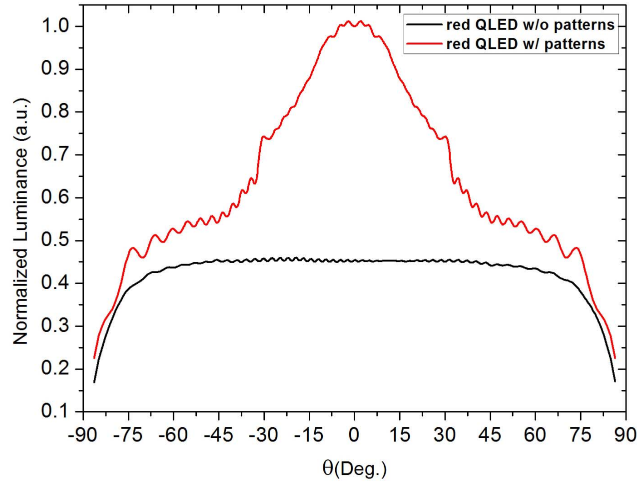

Figure 6. Luminance distribution of the red QLED with and without microstructures.

4. Color shift of the patterned QLED

Finally, the color shift of the patterned QLED is compared with the value of the conventional red QLED. Generally, periodic microstructures can enhance the outcoupling efficiency on the QLED while no significant color shift is introduced in the light-emitting element. Fig. 7 depicts the emission spectra at the viewing angle of 0^o, 30^o, and 60^o. It can be seen that the central wavelength is consistent even at large oblique angles. While the inhomogeneous broadened effect modifies the emission spectra of the QLED, it is not very noticeable because its PL spectrum is narrow and the periodic microstructures do not significantly influence the emission spectra. Fig. 8 compares the simulated color shift of a conventional red QLED and the proposed patterned red QLED in CIE1976. The Δu'v' is smaller than 0.02 even at 80^o, which is indistinguishable by the human eye. However, the radiated pattern is strongly angular dependent. This results in the broadening of spectra towards different viewing angles, especially at large viewing angles. Fig. 8 also reveals that a fluctuation of color shift appears at large angles. Fortunately the fluctuation is still lower than 0.02 and it is acceptable for human eyes.

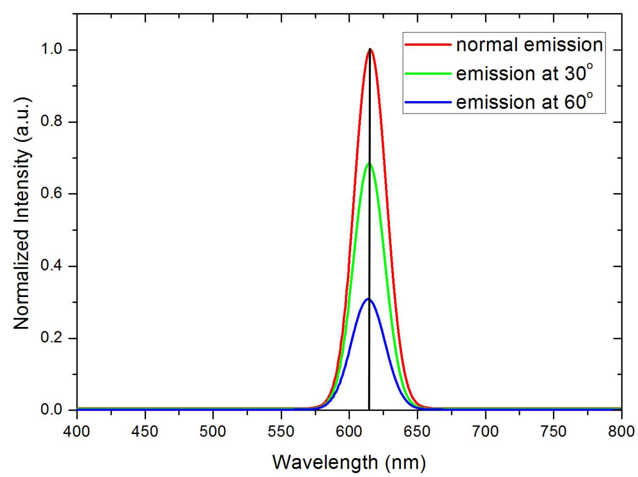

Figure 7. EL spectra of the patterned QLED at the viewing angle of 0^o, 30^o, and 60^o.

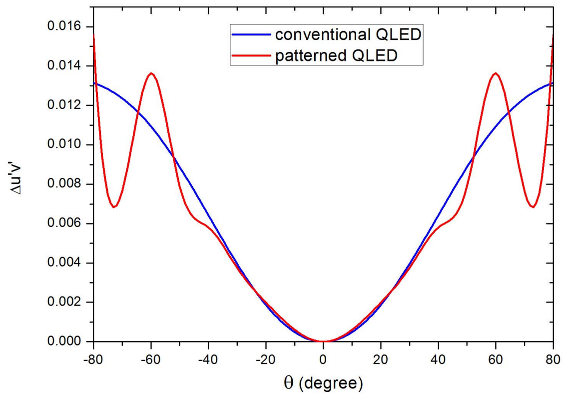

Figure 8. Calculated color shift of the conventional red QLED and the pattern QLED.

5. Summary

We have analyzed the outcoupling efficiency of QLEDs by using dipole model. In order to extract light as direct emission, a periodic microstructure is introduced into the QLED. Our FDTD analysis shows that a doubled enhancement on direct emission is achieved. The angular emission pattern and color shift of the patterned QLED are also analyzed. This approach can also be applied to optimize the performances of green and blue QLEDs. We confirm that periodic microstructures are able to enhance the outcoupling efficiency of QLEDs without the need of macroextractors, which is the advantage for QLED display.

6. References

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