Suppression of Blue Leakage in InP Quantum Dots for QD-LEDs and Modulation of Photoluminescence via Voltage-Driven Scattering Control

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Abstract

In this work, we propose suppression of blue leakage in quantum dot (QD) light emitting diodes and dynamic control of photoluminescence (PL) in liquid crystal (LC)-polymer-QD system. The LC droplets adjust scattering that can modulate PL emission from QDs. By reorienting LC, blue leakage and PL emission can be controlled and we were further able to suppress the blue leakage by adding Dye.

Author Keywords

Quantum dots (QDs); Quantum dots organic light emitting devices (QD-OLEDs); QD-LEDs; Blue leakage; Photoluminescence (PL); Polymerization induced phase separation (PIPS); Voltage-driven PL intensity modulation

1. Introduction

Quantum dot organic light-emitting diodes (QD-OLEDs) use blue OLEDs as light sources, and the blue OLED light is converted to green or red by pixelated QDs. However, some blue light is not converted completely during this process, resulting in blue light leakage [1–5]. To solve this problem, *M.S. Kim et al* reported liquid crystal (LC), polymer (P) and TiO_2 composites for reducing the blue leakage and enhancing the external quantum efficiency of photoluminescence (PL) [2]. In the optical properties of LC-P-QD ternary composite, LC droplets in the LC-P-QD composite play a role of scatterers to enhance PL emission. LC size over visible wavelength causes scattering, which is amplified by the mismatch of the refractive indices of the LC and polymer matrix [4–7]. As the voltage increases, LC reorients along the electric field direction, which is perpendicular to the plane of substrates. Then the scattering becomes suppressed which enables the modulation of both blue leakage and PL emission. In this state, the refractive indices of LC (n_o = 1.525) and prepolymer (n = 1.524) become similar and transparent state comes.

By replacing OLED to LED, the QD-LED displays prolong, but reduction in blue leakage becomes more important as the LED light intensity gets stronger. For resolving this issue, we propose additional dyes (D) putting together with LC-P-QD composites to further enhance the suppression of blue leakage.

In this work, we additionally propose dynamic control of blue leakage and PL intensity. These functions may provide interesting ideas to further design voltage-driven PL intensity control displays in case we can simplify the blue LED with no pixelated unit and LC-P(-Dye)-QD composites can be controlled by voltage instead of current driving. We believe this result can give some different approaches for voltage-driven dynamic PL displays.

2. Experimental

We prepared three different mixtures for LC-P-QD, LC-P-Dye, and LC-P-Dye-QD as shown in Table 1. The ratio between BL002 (T_{NI} = 71℃, n_e = 1.7710, n_o = 1.5250, Δn = 0.2460 at 589.3 nm, 20℃, Merck Advanced Technologies Co., Ltd.) and NOA65 (n = 1.524, maximum optical absorption at 350-380 nm by Norland Products Inc.) was fixed at 70/30 wt%. Also, we prepared LC-P-QD-dye quaternary mixture by adding an azo-dye (Disperse red 1, Sigma Aldrich Co.). The concentration of QD was fixed as 5 wt%, and the azo dye was added at 0.2, 1, 2, 5 wt% relative to the total mass of the composite. This was performed after the optimization of dye doped PDLC. The mixture was put in vacuum oven for 5 hours to evaporate the toluene. Then the mixture was injected into the unit cell consisted of two ITO (indium-tin oxide) coated glass substrates with 10 µm cell gap. The fabricated cell was cured under various UV conditions using a LED UV light source (HH200-sp4, U-Hitec Co., LTD.) with a peak wavelength of 365 nm. UV intensity was measured by a UV irradiance meter (UIT-201, Ushio).

Table 1. The sample variation of LC-P-QD, LC-P-Dye, and LC-P-Dye-QD.

	LC-P-QD				LC-P-Dye				LC-P-Dye-QD			
Name	Q1	Q2	Q3	Q4	D1	D2	D3	D4	DQ1	DQ2	DQ3	DQ4
NOA65 / [wt%]	28.57	27.3	26.1	25.0	29.9	29.7	29.4	28.57	28.5	28.30	28.0	27.3
BL002 / [wt%]	66.67	63.6	60.9	58.3	69.9	69.3	68.6	66.67	66.5	66.04	65.4	63.6
QD / [wt%]	4.76	9.1	13.0	16.7	-	-	-	-	4.8	4.72	4.7	4.55
Dispersed red1 / [wt%]	-	-	-	-	0.2	1	2.0	4.76	0.2	0.94	1.9	4.55
UV condition	A, B, C				A				A			

	UV condition A	UV condition B	UV condition C
UV irradiance / [mW/cm^2]	20	50	100
UV irradiance time / [min]	5	2	2

3. Results

As shown in Figure 1 and 2, when comparing the transmittance in the blue wavelength region and PL intensity before the voltage application and when the electric field strength increases up to 6 V/µm, we can see that the blue leakage and PL intensity changes. This means that the blue leakage and PL intensity are controlled from the initial state. As scattering decreases by increasing electric field strength, the PL of LC-P-QD composites decreases as shown in Figure 2. As the QD concentration increases, the initial blue leakage and PL intensity become higher, but the voltage-dependent blue leakage and PL intensity change ratio decrease. This is because the LC reorientation by applying voltage and scattering state change ratio is less effective when large amount of QDs exist together in the same layer. Through

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these results, we verify that the LC-P-QD can dynamically modulate the PL intensity.

In addition, we find the sample conditions (QD concentration of 5 w%, UV at 10 mW/cm^2 for 2 min) for the maximum values of blue leakage and PL intensity change ratio as shown in Figure 3.

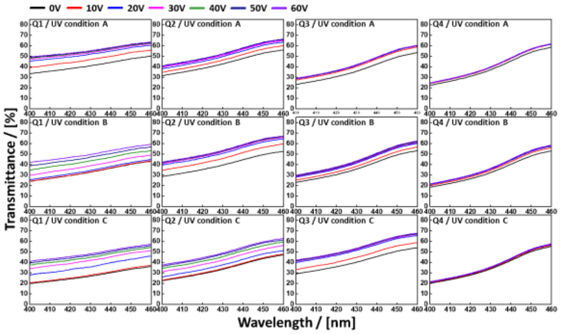

Figure 1. Verification of blue leakage in LC-P-QD composites measured in UV-Visible spectra when changing QD concentration, UV condition, and applied electric fields as the samples in the Table 1.

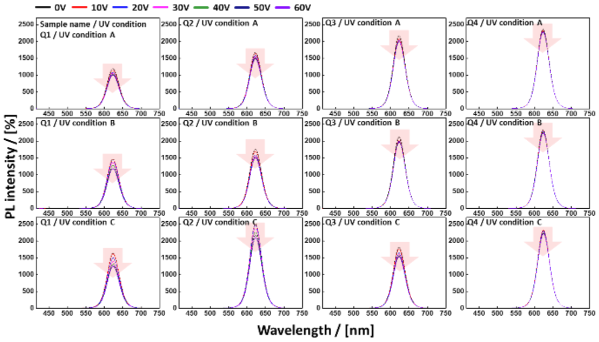

Figure 2. PL intensity change in LC-P-QD composites when changing QD concentration, UV condition, and applied electric fields as the samples in the Table 1.

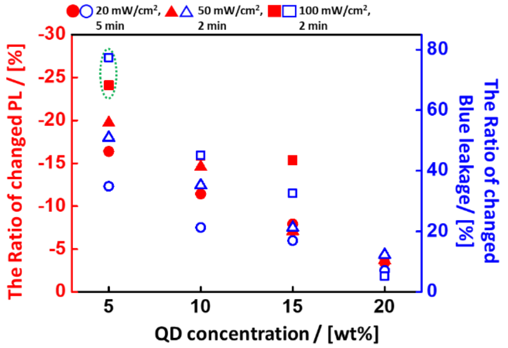

Figure 3. PL intensity and blue leakage level change ratio before and after applying voltage (6 V/μm) with various QD concentration and UV exposure.

We added an azo dye (Disperse Red 1, DR1) to selectively control light of specific wavelength range. In the case of DR1, it absorbs blue to green wavelength range and transmitting red colors. To observe the characteristics of DR1, we prepared four mixtures by adding 0.2, 1, 2, and 5 wt% of DR1 to a 70/30 (LC/P) in mixtures as arranged in Table 1. The UV exposure intensity was fixed at 100 mW/cm^2.

When applying the same electric field strength to this LC-P-Dye samples as we did to LC-P-QD, the transmittance in UV-Visible measurement shows significant change in blue wavelength range as shown in Figure 4. The initial level of transmittance in blue wavelength range is also significantly low. The difference in transmittance before and after voltage application is verified as well as the overall transmittance decreases as the concentration of the DR1 increases.

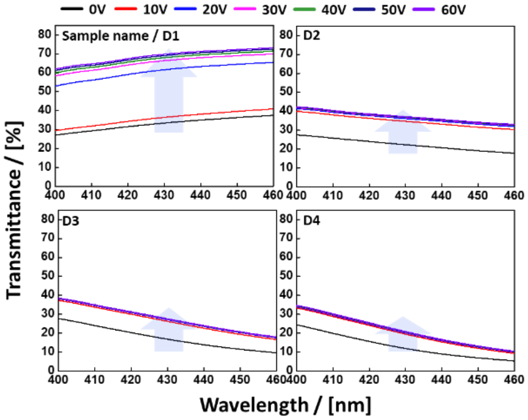

Figure 4. Transmittance graph according to dye concentration (400 - 460 nm).

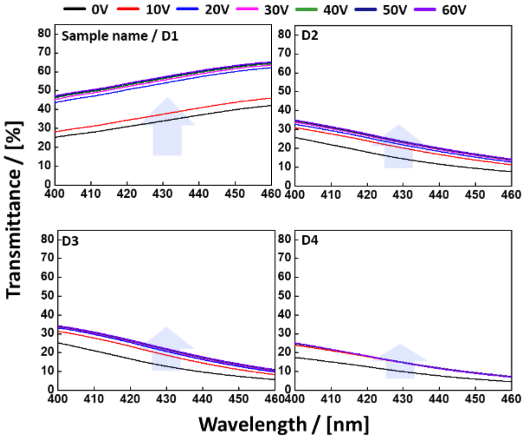

Figure 5. Blue leakage level of LC-P-Dye-QD according to dye concentration and when changing applied voltage.

The last samples consist of LC-P-Dye-QD as shown in Figure 5 and 6. The concentration of QD and UV condition was set to the same as the optimal conditions (QD concentration of 5wt%, UV exposure at 100mW/cm^2 for 2min). The concentration of dye was added with the same variation as LC-P-Dye samples. The blue leakage significantly decreases by increasing the DR1 concentration, as shown in Figure 5. In addition, although the effect is relatively less than that in the LC-P-QD samples, the blue leakage level changes as the applied voltage increases. The blue leakage change ratio decreases as DR1 concentration increases.

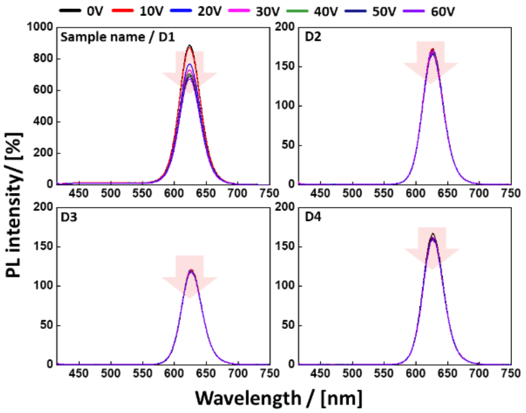

Figure 6. PL intensity change of LC-P-QD-Dye according to dye concentration and when changing applied voltage.

The PL intensity also decreases as DR1 concentration increases. However, the level of PL intensity is quite competing when the DR1 is 0.2wt%. The PL intensity change ratio is also relatively higher at smaller concentration of DR1.

4. Discussion

In this study, we demonstrated the suppression of blue leakage and the modulation of PL intensity in QD-LEDs during color convergence by fabricating QD-LC-P, LC-P-Dye, and LC-P-Dye-QD samples. These samples were designed to control scattering states, thereby enhancing color conversion efficiency. Our results reveal that the blue leakage and PL intensity can be effectively controlled by applying voltage to the LC-P composite system, which transitions between opaque and transparent states. Furthermore, the addition of red dyes, which absorb blue wavelengths, significantly reduces blue leakage. While increasing the dye concentration decreases overall PL intensity, it achieves substantial blue leakage suppression. Based on these findings, we propose optimal parameters for balancing blue leakage and PL intensity to meet the requirements of various device applications. Additionally, we demonstrate that modulating the scattering state in the LC-P composite system can influence PL intensity, effectively impacting the external quantum efficiency for color conversion. This approach highlights a novel, voltage-driven pathway for the development of PL-based display technologies, offering innovative insights for next-generation display systems.

5. Impact

QD-LEDs represent a promising next-generation display technology capable of addressing the lifetime challenges faced by current QD-OLEDs. Building on the results presented in this study, we propose an alternative approach to suppress blue light leakage, a critical issue in QD-OLED fabrication and performance. By incorporating dyes into the same layer as the QDs, blue light leakage can be effectively mitigated, potentially eliminating the need for additional color filter layers and simplifying the fabrication process. For the first time, we introduce voltage-driven (indirect) control of PL intensity, offering a novel method to modulate PL in light-emitting displays. This concept could enable different display architectures, such as non-pixelated LED backlights combined with a pixelated LC-P-QD layer driven by voltage instead of current. Such a design holds the potential to suggest a new display concept by utilizing PL rather than electroluminescence, thereby achieving higher light conversion efficiency. We believe this approach can open new pathway for controlling emitted light and advancing the development of next-generation display systems.

6. Acknowledgements

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