Optical Efficiency Improvement of QD-OLED Technology with Structural Design and Material Selection

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Abstract

The low light extraction efficiency of QD-OLED restrict its wide application in high-resolution full-color display. Optical structural design optimization of the relative width and distance of quantum dot & blue-OLED cells, the introduction of the refractive-matching material and selective optical films are utilized to solve this problem. On the whole, a >40% efficiency improvement and >90% coverage of BT. 2020 color gamut have been achieved.

Author Keywords

Quantum Dot color conversion, light extraction efficiency, Thin Film Encapsulation, QD-OLED, BT. 2020

1. Introduction

Display technology has become increasingly important in our daily life, with widespread applications in small- and medium-sized smartphone, tablets, large-sized monitors, TVs, etc. Currently, liquid-crystal (LC) displays and organic light-emitting diode (OLED) displays [1] are two main commercial products. The rising visual expectations of consumers promote the increasing demand for high-quality full-color display technology.

A wider color gamut provides a better visual perception, as important as brightness, consisting the high-quality display. The International Telecommunication Union Radio communication Sector (ITU-R) released the next generation ultra-high-resolution display standard BT.2020 in 2012 [2], which can reproduce approximately 99.9% of colors in nature. However, the absence of red, green and blue emitting materials which fully conform to the spectrum of BT.2020 make it difficult to achieve the absolute BT.2020 color gamut. For this reason, the research that accommodate the BT.2020 color gamut mostly focus on quantum dot displays and laser displays [3-6].

Full-color representation is generally realized by mixing red, green, and blue color primaries through three ways: RGB tri-color independent luminescence, white-OLED with color filter, and the utilization of a blue excitation light source with quantum dot (QD) color convert. However, these three kinds of technologies face different obstacles, the high-specification accuracy alignment in evaporation and fabrication dimension of the fine metal mask (RGB-OLED); the precise optical design to meet red, green, blue tri-color micro cavity requirement in one device structure (white-OLED); relative lower efficiency and shorter lifetime blue-fluorescent material, and lower quantum dot color conversion efficiency (QD-OLED).

As for an alternative approach to wider color gamut reproduction, Quantum Dot color-conversion technology utilize blue light to convert to red and green light. This technology relies on the photoluminescence of the blue-excitation source and quantum dot materials. Currently, extensive research [7-8] is focused on the color-conversion Micro-LED technology, which believed to be a feasible commercializing pathway. However, the fabrication process and device design for color-conversion Micro-LED are still uncertain. Meanwhile, Color-conversion OLED TVs have already been commercialized by companies like Samsung and Sony, but the scientific research is limited due to the proprietary nature of the emerging technology.

Furthermore, different from high-luminance and long-lifetime inorganic blue-LED excitation source, a relative lower-efficiency and shorter-lifetime blue-fluorescent OLED excitation source make it especially important to optimize the design to maximize the light extraction efficiency. This paper focus on the structure design and material selection in high-resolution pixelated full-color display, in order to improve the QD color-conversion efficiency and color gamut.

2. Device Structure

Different from the present commercial QD-OLED products, which quantum dot are fabricated on cover glass and laminated onto the Blue-OLED cell, the quantum dot on encapsulation structure offers an opportunity to improve the light extraction efficiency and extend to high-resolution applications. Off course, this process need higher-specification low-temperature quantum dot materials, to reduce the influence of lithography process on OLED.

As shown in Figure 1, the QD-OLED display contains three parts, (a) 3-stacked top-emitting Blue OLED (Blue-OLED), (b) Quantum Dot color conversion (QD), (c) Color Filter (CF), which are connected by different inorganic and organic material assembled as TFE1&2.

For Blue-OLED part, blue fluorescent material and 3-stacked tandem device structure are fabricated as excitation light source; the second part introduce a thickness of approximately 5μm QD layers to meet high resolution requirement; meanwhile, three color filters are introduced to remove unconverted color.

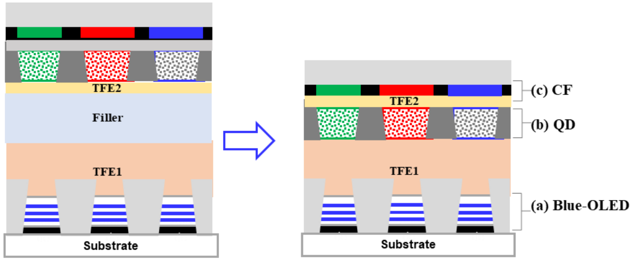

Figure 1. Structure design of QD on Cover Glass and QD on Encapsulation Display Technology.

3. Results and Discussion

In this section, the structure design including (a) the thickness of encapsulation layers, the relative width of QD and Blue-OLED cells, (b) the material selection of the refractive-index layer adjacent to the QD layer, (c) the optical selective transmittance-reflection characteristics of the encapsulation layer are discussed in pixelated full-color display design.

(a) Optimal structural Design in order to improve higher QD conversion efficiency

As shown in Figure 2, the relative distance and width of QD and Blue-OLED cell change the amount of excitation light incident to the QD color conversion film, and the optical leakage ratio into the adjacent sub-pixel. Higher coverage of quantum dot will improve the conversion efficiency and total light extraction, but cannot be applied in high-resolution displays. Additionally, limited by the underlying insulation structure and flattening material characteristics, a relatively thicker organic film is applied in TFE1, in order to ensure the encapsulation effect.

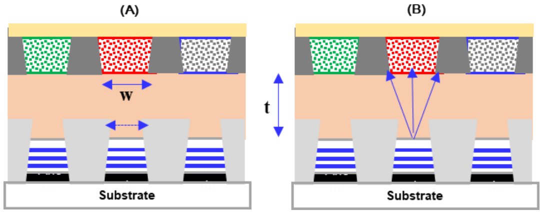

Figure 2. Two variable structural diagrams of QD-OLED display, (A) the thickness of TFE1, (B) the relative width of QD and Blue-OLED cell.

Based on the above-mentioned analysis, we adjusted three different relative widths of QD and Blue-OLED cells (Figure 3-(A) & (B)). The target conversion red and green color tend to go up 20~50% (w1 < w2 < w3, increased by 2μm).

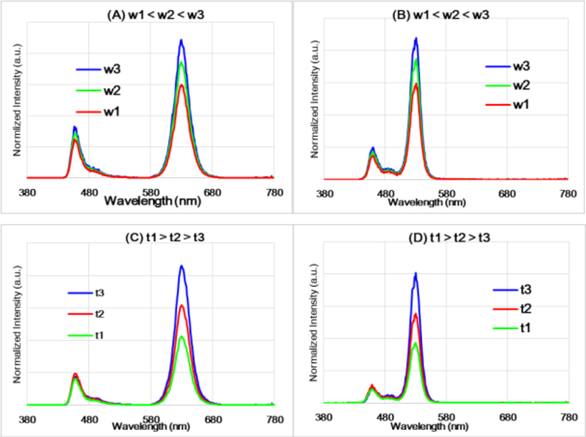

Figure 3. Efficiency improvement of red and green color by structural optimization of QD and Blue-OELD cell.

Besides the increased width, we further altered the thicknesses of thin encapsulation film (TFE1). As shown in Figure 3-(C) & (D), thickness reduction of TFE1 (t1 > t2 > t3, decreased by 4μm) bring > 40% improvement of target color efficiency.

Finally, an appropriate balance between current flatting organic material, and target color efficiency have been done by the structural adjustment of encapsulation layer and QD color-conversion layer coverage.

(b) Low refractive-index material selected to promote QD conversion efficiency

On account of incomplete conversion from blue-excitation light to target red & green conversion light, three color filters have been adopted to enhance color purity. Normally, the computation spectrum before and after color filter agree with the experimental data, just multiplied by the transmission spectrum of corresponding color filter.

But in our real experiments, the OLED + QD + CF (all experimental) show a 20~30% efficiency reduction, compared with the OLED + QD multiplied by Color Filter transmission spectrum. As shown in Figure 4-(A) & (B), the target green and red color show a similar efficiency reduction.

So, a nearly 100% high transmission red color filter and different refractive-index encapsulation layer upon QD layer have been simulated to identify the cause of the deviation. In Figure 4-(C), the spectrum of OLED + QD + CF (* CF_High_T) is the same with the OLED + QD. But the simulation data reveals a >30% efficiency reduction.

The change of the refractive-index encapsulation layer upon QD layer show a target color efficiency increase in Figure 4-(D) (Simu.1 & Simu.2). A further decrease of the refractive-index encapsulation layer possess a continuous efficiency improvement.

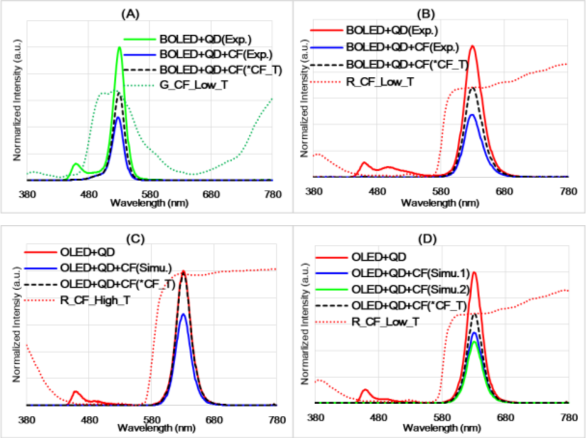

Figure 4. Spectrums of Blue-OLED + QD + CF, experimental vs. simulation vs. multiplication computation**.**

The refractive-index of the encapsulation layer on QD affect the color conversion has been reported in several papers [9]. Moreover, in the process of scattering-QD and CF cells integration, the refractive-index mismatch will produce a different experimental data with the conventional computational method without scattering-particles.

Therefore, the low refractive-index layer become an essential solution for quantum dot color conversion improvement. It acts as not only the role of bouncing more unconverted blue light to scattering quantum dot layer, but also as the role of index-matching layer reducing unnecessary losses of the converted red or green color emitting backward into scattering quantum dot layer again.

(c) Dielectric Filter introduced to recycle converted red and green

On the basis of the above analysis, the converted red or green color will emitting backward to the Blue-OLED cell and be wasted on account of microcavity effect. So, a dielectric filter (distributed Bragger Reflector, DBR) has been designed to reflect the converted target color and transmit the excitation blue color (Figure 5-(A) & (B)).

Three and four pairs of dielectric films are specifically designed to realize selective transmittance-reflection characteristics (Figure 5-(C)). From the spectrums, we can find >50% reflectance at 530 nm and 630 nm, and <10% at 450~460nm excitation light range.

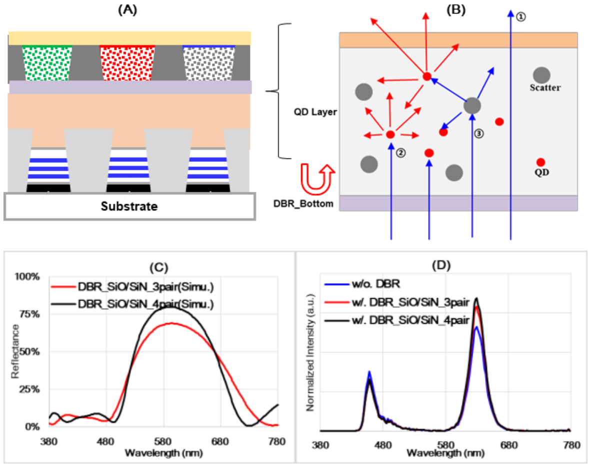

Figure 5. Efficiency improvement by Distributed Bragger Reflector**.**

Meanwhile, the dielectric layers are fabricated by conventional chemical vapor deposition, mainly consist of low-refractive SiOx and high-refractive SiNx films. Introducing the DBR structure into QD-OLED technology, a >15% efficiency increase has been achieved, as shown in Figure 5-(D).

The optimization of structure design and careful selection of materials act together improve the quantum dot color conversion and the total light extraction. In addition, these design contribute to the reduction of optical crosstalk and the color gamut enhancement (increase from 60% to 91% cover ratio (BT. 2020)). (As shown in Figure 6 & 7)

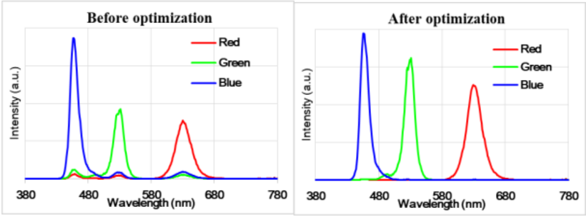

Figure 6. Improvement of extraction efficiency and reduction of optical crosstalk before and after optimization**.**

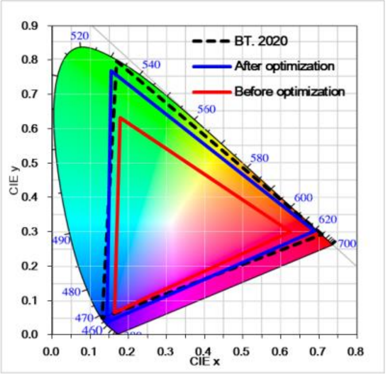

Figure 6. Color gamut diagram of optimized QD-OLED**.**

4. Conclusion

In this paper, three decisive factors have been explained to improve the existing quantum dot color conversion efficiency and color gamut in QD-OLED technology.

A 20~50% efficiency increment can be obtained by the reduction of thin encapsulation film and the optimization of relative width of quantum dot & blue-OLED cells. Meanwhile, the refractive-matching material and selective optical films have been fabricated to achieve a further 15% increment. Finally, a total >40% efficiency improvement have been obtained, while color gamut enhanced from 60% to 91% coverage of BT. 2020 super color gamut.

Moreover, substantial intensive research into high resolution, low cost, high reliability and the photoluminescence of the blue-excitation source and quantum dot color-conversion will be essential to the development of high-resolution, high-specification commercial products in this filed.

5. References

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