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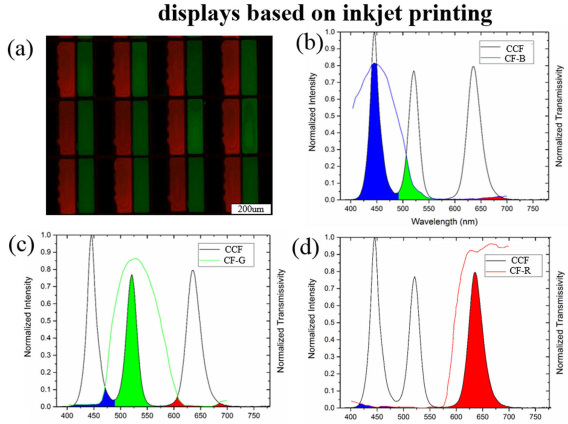


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# Color Converting Film With Quantum-Dots for the Liquid Crystal Displays Based on Inkjet Printing

**Bing-Le Huang** [1,2] **Tai-Liang Guo,** [2] **Sheng Xu,** [2] **Yun Ye,** [2]
**En-Guo Chen** [2] **and Zhi-Xian Lin** [2]

[1]Department of Information Engineering, Fujian Chuanzheng Communications College, Fuzhou 350007, China
[2]College of Physics and Information Engineering, Fuzhou University, Fuzhou 350002, China

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**Abstract:** The color converting film (CCF) is first fabricated by the inkjet printing technology with the drop-on-demand advantage in the paper, the volume ratio of the red quantum-dots (QDs) over green QDs is 1:12.9 at balanced intensity, and each subpixel of the CCF is sprayed with five droplets with each volume of 48 pL. The CCF has been equipped in the corresponding liquid crystal display (LCD) module. In theory, the optical efficiency of the CCF mainly depends on the quantum yield of QDs, therefore, and the total optical efficiency can improve by 2.4 times. The LCD module sample has been tested to verify the performance. Experimental results show that the color gamut reaches 131.4% NTSC in CIE 1931, the total optical efficiency is 20%. Comparing with the wide color gamut backlight module with QDEF, the color gamut improves by 16.4% NTSC, the total optical efficiency improves by 2.1 times, and the average color crosstalk ratio decreases by 4.21% under the condition that the misaligned size is larger than the width of the black matrix. Our method provides theoretical guidance to realize high-performance LCDs.

**Index Terms:** Wide gamut, color converting film, inkjet printing, color crosstalk.

## 1. Introduction

Backlight is a key component of liquid crystal display (LCD) devices, due to its influence on the main performance including optical efficiency, color gamut, viewing angle, and dynamic range, etc. [1]–[6]. In the past two decades, the light source for the backlight has developed from cold cathode fluorescence lamp (CCFL) to phosphor-converted white light emitting diode (1pc-WLED), bringing about significant improvement for both volume simplification and life-time prolongation [7],

[8]. However, the broad yellow spectrum leads to a relatively narrow color gamut 75% of the National Television Standard Committee (NTSC) standard in Commission Internationale de l'Elcairage (CIE) 1931 color space. Similar to 1pc-WLED, two phosphor-converted WLED (2pc-WLED) should be the most common commercialization method to extend color gamut and improve optical efficiency [9]–[12]. The mixture phosphors can be easily packaged above a tiny semiconductor chip and it exhibits advantages in low cost, outstanding stabilization and long lifetime. But the full width at half maximum (FWHM) for the green phosphor always maintains at about 55 nm [12], [13], and serious crosstalk level will occur while the red (R), green (G) and blue (B) lights passing through the color filters (CF). That reduces the color purity correspondingly.

Unlike the phosphors, quantum-dots (QDs) are semiconductor particles with nanometers in size, whose position of the peak central wavelength (PCW) and bandwidth of the FWHM for the spectrum excited by QDs can be tunable by changing their size, shape, distribution and composition. Recent researches report that the QD-enhanced film (QDEF) equipped in backlights offers an alternative approach to extend the color gamut and improve the optical efficiency of the LCDs [14]–[17]. For examples, Luo analyzed the color performance and system efficiency of three commonly employed liquid crystal display modes with a blue LED-pumped red and green QDs backlight [18]. It achieved 115% color gamut in CIE 1931 while keeping the same energy efficiency as conventional backlights. Chen proposed a new backlight system, and the backlight achieved 95.8% Rec. 2020 in CIE 1931 color space with commercial high-efficiency color filters by incorporating a functional reflective polarizer and a patterned half-wave plate to decouple the polarization states of the blue light and the green/red lights [19], but the backlight needs additional functional reflective polarizer to stop the blue light entering the green and red CF region.

Although the QD backlight can improve the color gamut for the LCD, the LCD will waste two third of the optical energy when the primary colors pass through the CF. In order to further extend the color gamut and improve the optical efficiency, Liu proposed a quantum dot array, and Lee proposed ambient processing of quantum dot photoresist for emissive displays, but the actual performance for the backlight employing the QD film was not presented [20], [21]. Zhou proposed a method to make QDs better dispersed in the CF resin, enlarging the color gamut of the film to 119% NTSC [22]. A patterned QD film was developed by Kim to obtain 95% of the Rec. 2020 color gamut [23], but they did not analyze the color crosstalk after the light pass through the CF. Lee reported that the blue light transmission reduced to 0.4% when the film thickness for green QDs was 6 micrometers; [24] but there are still some unconverted blue light passing through the QDs film. Among current researches, wide color gamut and high spectral efficiency are always expected to be simultaneously achieved for LCDs.

Based on the analysis discussed above, this paper firstly presents the principle of color converting film (CCF) and the structure of the LCD module (LCM) with the CCF, the optical efficiency for the color conversion mainly depends on the quantum yield of QDs, and the geometric arrangement and absorption properties may affect the optical efficiency at a certain extent [25]–[27]. Therefore, the sample can provide higher efficient and wide gamut performance; then the fabricated process of the CCF based on inkjet printing has been proposed in detail, and finally the sample has been tested and analyzed. As we know that the quantum yield of QDs is around 80%, but the optical efficiency of the color conversion for the CF is less than one third, therefore, the CCF equipped in LCM can observably promote the optical efficiency based on the process of the color conversion. In theory, the total optical efficiency can improve by 2.4 times.

## 2. Experiment

### *2.1 Fundamental Model of the CCF*

The CCF with wide color gamut and highly efficiency is proposed in Fig. 1. Fig. 1(a) describes the schematic structure of the CCF comprised of three microstructure arrays of red/green/blue subpixels, and the black color represents black matrix. The red and green subpixels are filled with the corresponding QDs. The blue subpixel is empty, so that the blue collimated light emitted from

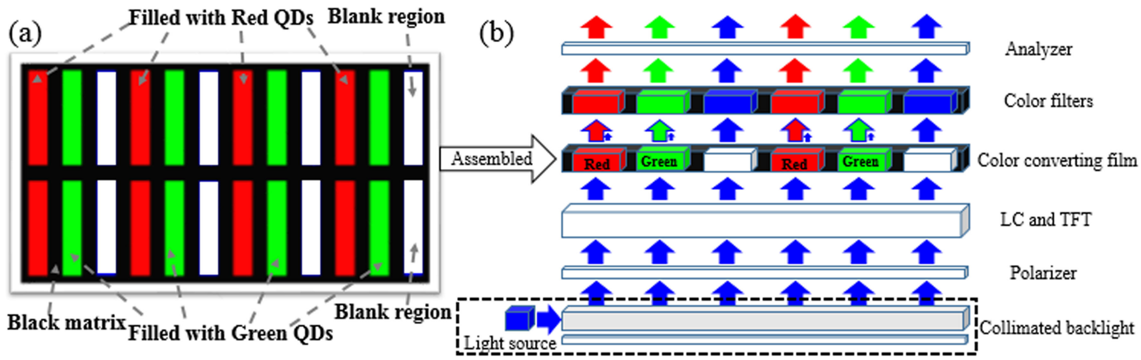


Fig. 1. (a) Schematic structure of the CCF. (b) The proposed CCF assembled in an LCM.

the backlight will pass through the blue subpixel without any conversion. The black matrix can help to reduce the color crosstalk. Fig. 1(b) maintains the principle of the light conversion in the experimental LCM. The red and green light will be excited from the red and green subpixels by the down conversion of the blue backlight, the output red and green light from the subpixels are not pure. The traditional CF can help filter the mottle. Although the traditional CF can improve the color purity, it will decrease the optical efficiency and the luminance. Therefore, other designs such as short-band pass filters or distributed Bragg reflectors can reduce the unconverted blue light without sacrificing the optical efficiency; [28] but these method cannot completely eliminate the unconverted blue light that pass through the red and green QDs area. And the main purpose of the experiment is to verify the CCF with QDs by inkjet printing is feasible. Hence, we adopt traditional CF to complete eliminate the unconverted blue light. In this procedure of the light conversion, the light energy will not be wasted like traditional LCM, and the optical efficiency mainly depends on the quantum yield of QDs. Compared to traditional QD backlights, the proposed LCM has apparent advantage of improving the optical efficiency while reducing color crosstalk.

### 2.2 Preparation Process

The CCF proposed in the paper was fabricated by adopting inkjet printing technology, since the drop-on-demand (DOD) and direct writing process can be easily provided. The inkjet printing process is performed by Jetlab II (MicroFab Technologies, Inc). The diameter of the nozzle is 30 $\mu$m. As a reference, the optimum viscosity for inkjetable fluids in piezoelectric DOD inkjet printing reported in literature is 3–20 mPa·s [29], [30]. Therefore, the fluids for QD solution should satisfy the requirement. The subpixel parameters of the CCF are given as follows. The length and width of each pixel are 297 $\mu$m and 99 $\mu$m, respectively. The wall width and height of the pixel are 20 $\mu$m and 1 $\mu$m.

The powders of QDs and dispersant were prepared with the PCW of 520 nm/635 nm for green (ZnCdSe/ZnS)/red (CdSe/ZnS) and the FWHMs of both 30 nm. The pixels were fabricated by photolithographic process. The dispersing liquid for the QDs can be cured under 365 nm UV light condition with 12 mW/cm$^2$ for 10 minutes at room temperature.

The concentration of the red and the green QDs dispersant are the same, and we only adjust the volume of the two QDs dispersant. The volume ratio of QD solution is adjusted to balance red/green light intensity. Fig. 2 shows the matching process of the red/green relative intensity measured by FL4600 (Hitachi Limited). It is clearly seen that the relative intensity of the emitted light varies with the volume change. The PCW of the excitation source was set at 447 nm. When the emitted intensity reached a balance, the volume ratio of the red QDs over green QDs was finally 1:12.9. As shown in Fig. 2(b), the matching relation between the emitting intensity of red/green light is irrelevant to the photomultiplier tube (PMT) voltage, which is the voltage value applied to the lamp in the fluorescence spectrophotometer.

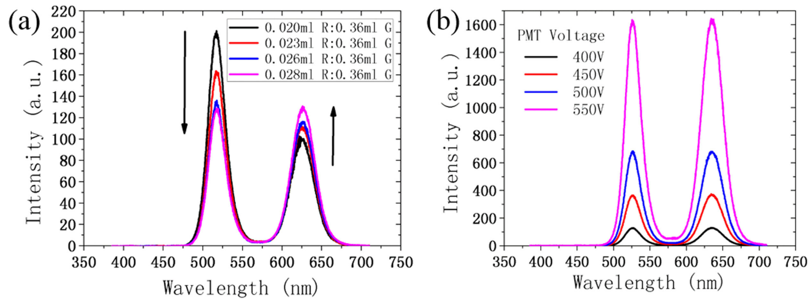


Fig. 2. (a) The matching of green/red relative intensity with the concentration adjustment. (b) The relationship between the emitted light intensity and the PMT voltage.

TABLE 1
Proportion for the Concentration

| QDs | Concentration | Viscosity |
|---|---|---|
| red | 2.16mg/ml | 3.29 mPa·s |
| green | 27.8mg/ml | 4.59 mPa·s |

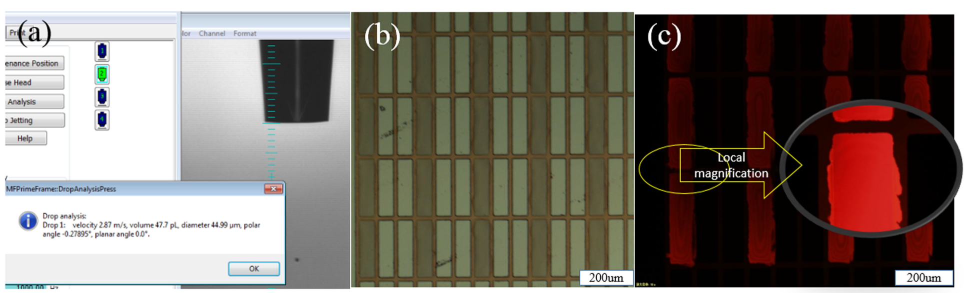


Fig. 3. (a) Screenshot for the inkjet drop adjustment. (b) Local microscope picture under the white light; (c) local microscope picture under the blue light.

The concentration and viscosity for the dispersing liquid were listed in Table 1 according the equilibrium condition discussed above.

Fig. 3 describes the procedure and results of the inkjet printing, Fig. 3(a) shows the parameters when the droplet is stable. The partial enlarged microscope picture of the red subpixels, shown in Fig. 3(b) and (c), were observed under white light/blue light source excitation, respectively. In the process of the inkjet printing, each subpixel was sprayed with five droplets, and the volume for each droplet was approximately 48 pL shown in Fig. 3(a). The outcome for the inkjet printing with red QD dispersing liquid was obviously seen from Fig. 3(b) and (c).

### *2.3 Results*

The test conditions are described as follows: the spectra of the sample are tested by SRC-200M (Everfine Co., Ltd.) in the darkroom. Fig. 4(a) shows the partial enlarged microscope picture of the droplet covering the empty subpixels after the inkjet printing the two kinds of QDs dispersing liquid. Fig. 4(b) is the picture of the lightened LCM sample.

Fig. 5(a) is the normalized transmissivity distribution of the CF commercially employed. Fig. 5(b)–(d) shows the relationship between the spectrum of the sample and the transmissivity of the CF.

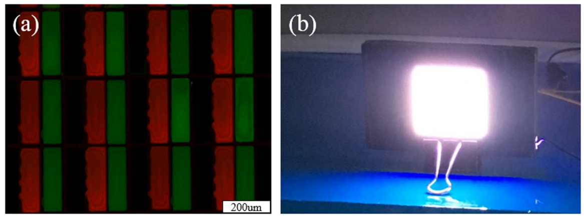


Fig. 4. (a) Partial enlarged microscope picture for the contiguous subpixels under the blue light excitation. (b) The picture of the lightened LCM sample.

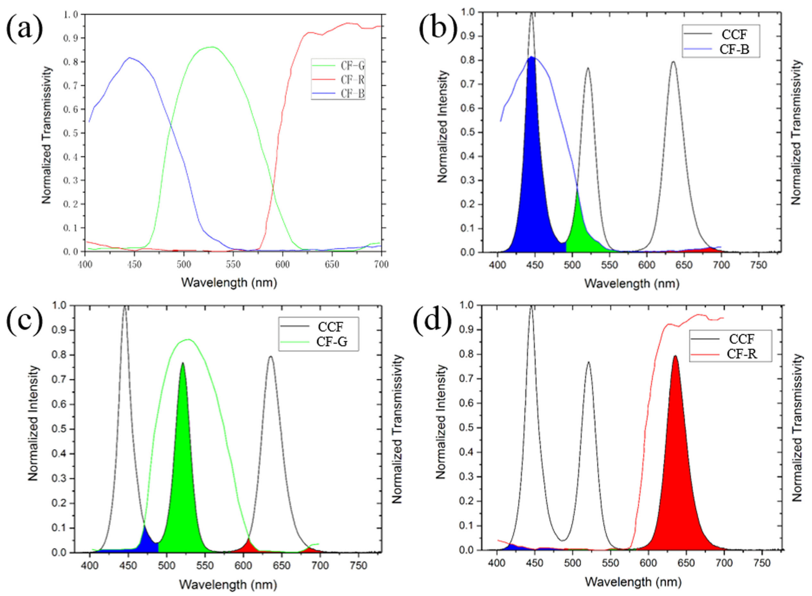


Fig. 5. (a) Normalized transmissivity distribution of the CF commercially employed. The relationship between the spectrum of the sample and the transmissivity distribution of the CF. (b) The blue subpixels of the CF (CF-B). (c) The CF-G. (d) The CF-R.

The color gamut is calculated to be 131.4% NTSC in CIE 1931 according to the spectral data shown in Fig. 5. The luminance for the backlight and LCM are 3678 cd/m$^2$ and 736 cd/m$^2$ tested by SRC-200M (Everfine Co., Ltd.), respectively; the corresponding optical efficiency is 20%. The above experimental results demonstrate the structure for the LCM and the inkjet print process is effective.

## 3. Analysis and Discussion

The color purity of LCD displays is primarily affected by the matching between the output spectrum of backlights and the transmissivity distribution of the CFs within the LC cell. Therefore, the color crosstalk comes from the mismatching of three primary color passing through the adjacent subpixels of CFs to a great extent. Take the LCD backlight using a 1pc-WLED as the light source for example. Fig. 6(a) draws the emission spectrum of this backlight. The emission spectrum of the 1pc-WLED and the transmissivity distribution of the CF are commercially employed, which have been reported in Ref. [12].

As can be seen from Fig. 6(b)–(d), the spectra of primary colors and the CF transmissivity show an obvious mismatch so that serious color crosstalk would exist in the blue-green and green-red spectral regions. It deteriorates the output color purity and wastes a majority of light energy. As a

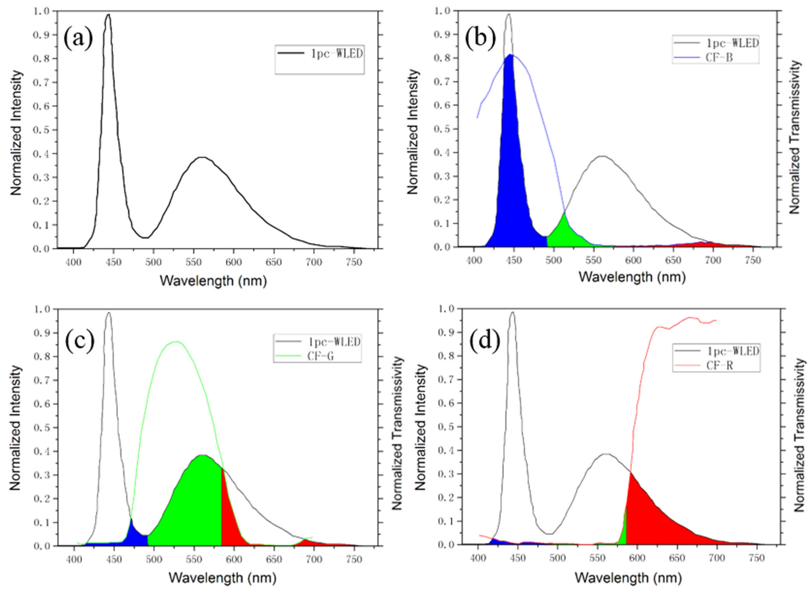


Fig. 6. (a) Normalized intensity of the emission spectrum for an LCD backlight equipping a 1pc-WLED. (b)–(d) The final output spectrum for the three primary colors.

result, the largest color gamut using a 1pc-WLED is only around 75% NTSC in CIE 1931, and the maximum optical efficiency is 8.7% in reference [18].

From the above analysis, the backlights using the 1pc-WLED, are hard to avoid color crosstalk and low light efficiency. This problem can be solved by the QD-enhanced backlight to some extent. As we know that a QD backlight has a high color gamut with the maximum optical efficiency around 9.7%. The efficiency is roughly the same as the 1p-WLED that was reported in reference [18]. The main reason for this is described as follows.

The normalized intensity of the spectrum for a commonly commercial backlight module equipping a QDEF is shown in Fig. 7(a). The spectral characteristics of QD-enhanced backlight provides a narrower emission peak of the three primary colors, which is better than 1p-WLED. At the same time, Fig. 7(b)–(d) depict the matching relationship between the spectra of three primary colors and the CF transmissivity, respectively. It is clearly seen that there still exists the similar color crosstalk especially between the blue and green spectral region. The light leaking through the blue and green subpixels of CFs undoubtedly reduces the final color purity and loses large amounts of light energy. That should be the main reason that the color gamut cannot reach the theoretical level for the QDEF-enhanced backlights [16].

The CCF proposed in the paper can obviously reduce the color crosstalk mentioned above in theoretically, the reasons are as follows. As shown in Fig. 1(b), the light conversion of the red and green has been restricted in the lattice of the CCF, and the light of the three primary colors will not come cross in the help of the black matrix. If the CCF is misaligned with the color filter array, the light energy will be resisted by the color filter array, and color crosstalk will happen when the size of the misplacement exceed the maximum tolerance. The maximum tolerance for the misalignment is the width of the black matrix, because if the size for the misalignment is less than the width of the black matrix, it will only induce light energy loss; but if the size is larger than the width, it will not only induce light energy loss, but also bring color crosstalk.

In order to compare the color crosstalk with the others when the size of the misplacement exceeds the maximum tolerance, we define the color crosstalk ratio (CCR) in the following formula:

$$\mathrm{CCR} = \frac{CCIA}{PIA} \times 100\%. \tag{1}$$

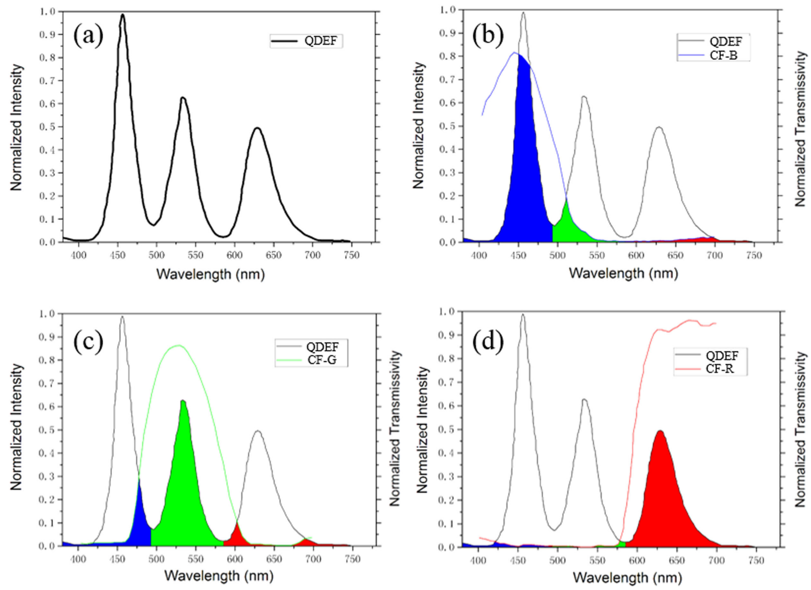


Fig. 7. (a) Normalized intensity of the emission spectrum for QD-enhanced backlight. (b)–(d) The final output spectrum for the three primary colors.

TABLE 2
Color Crosstalk Ratio for the LCM Equipping a 1pc-WLED, a QDEF, and the CCF

| Item | Primary color | CCIA | PIA | CCR(%) | Average CCR(%) |
|---|---|---|---|---|---|
| 1pc- | Blue | 5.9285 | 23.6298 | 25.09 | |
| WLED: HP | Green | 8.0621 | 25.0921 | 32.13 | 23.60 |
| Pavilion 23 | Red | 2.0392 | 15.0132 | 13.58 | |
| QDEF: | Blue | 6.3583 | 27.1081 | 23.46 | |
| Samsung | Green | 7.4124 | 23.605 | 31.4 | 20.63 |
| Q8C | Red | 1.6638 | 23.6247 | 7.04 | |
| HECCF: | Blue | 5.8067 | 24.9707 | 23.25 | |
| Sample | Green | 4.1532 | 19.7252 | 21.06 | 16.42 |
| | Red | 1.3577 | 27.4118 | 4.95 | |

where, CCIA represents the integral area for the color crosstalk, and PIA represents the integral area for the primary color. The integral area is the shadow area with colors in Fig. 5(b) to (d)–Fig. 7(b) to (d). They are separated by wavelength. The wavelength for blue is from 380 nm to 490 nm, the wavelength for green is from 490 nm to 586 nm, the wavelength for red is from 586 nm to 780 nm.

The CCR values for the backlights equipping a 1pc-WLED, a QDEF, and the CCF are listed in Table 2. It is obvious that the color crosstalk of green light is higher than others. The reason is that the bandwidth of the green transmissivity of the CF is wide.

The average CCR for the QDEF exceeds 20%, which is 3% lower than that for the 1pc-WLED. This can explain why its color gamut cannot realize the theoretical value. And the CCR values for the CCF are calculated under the condition that the misaligned size is larger than the width of the black matrix. Compared to the data for the backlights equipping a 1pc-WLED, a QDEF, it is obvious that the average CCR of the CCF is the lowest among them. The average color crosstalk ratio value of the CCF is only 16.42% under the condition that the misaligned size is larger than the width of the black matrix, which is much lower than that of 1pc-WLED and QD-enhanced backlights. The optical efficiency of the sample is 20%, Comparing with the wide color gamut backlight module with QDEF, the color gamut improves by 16.4% NTSC, and the total optical efficiency improves by 2.1 times. The reason for the total optical efficiency not reaching the theoretical value is that the CCF's geometric arrangement and absorption properties can affect the efficiency at a certain extent [25]–[27]. Therefore, our method provides theoretical guidance to realize pure colored and energy-efficient LCDs.

## 4. Conclusion

The CCF was firstly fabricated by the inkjet printing technology with the DOD advantage, and the volume ratio of the red/green QDs is 1:12.9 at balanced intensity. Each subpixel of the CCF is sprayed with five droplets with each volume of 48 pL. The CCF was assembled into an LCM and measured under the excitation of blue backlight sources. The experimental results show that the color gamut reaches 131.4% NTSC in CIE 1931, better than the commercial QDEF backlight solution. The average color crosstalk ratio value of the CCF is only 16.42% under the condition that the misaligned size is larger than the width of the black matrix, which is much lower than that of 1pc-WLED and QD-enhanced backlights. The total optical efficiency of the sample is 20%. Comparing with the wide color gamut backlight module with QDEF, the average color crosstalk ratio decreases by 4.21%, the color gamut improves by 16.4% NTSC, and the total optical efficiency improves by 2.1 times. Therefore, our method provides theoretical guidance to realize pure colored and energy-efficient LCDs.

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