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Ultra-High Light Extraction Efficiency and Ultra-Thin Mini-LED Solution by Freeform Surface Chip Scale Package Array

Che-Hsuan Huang [1,2], Chieh-Yu Kang [1], Shu-Hsiu Chang [2,3], Chih-Hao Lin [1], Chun-Yu Lin [2], Tingzhu Wu [4,*], Chin-Wei Sher [1,5], Chien-Chung Lin [3], Po-Tsung Lee [1] and Hao-Chung Kuo [1,*]

1 Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan; daniel.huang@leda-creative.com (C.-H.H.); kangcy1026@gmail.com (C.-Y.K.); actupon@gmail.com (C.-H.L.); steven.sher@hotmail.com (C.-W.S.); potsung@mail.nctu.edu.tw (P.-T.L.)
2 LEDA-creative Co., Ltd., No.45, Zhengyi Rd., Pingzhen Dist., Taoyuan City 32457, Taiwan; Frank.chang@leda-creative.com (S.-H.C.); jim.lin@leda-creative.com (C.-Y.L.)
3 Institute of Photonic System, National Chiao Tung University, Tainan 711, Taiwan; chienchunglin@faculty.nctu.edu.tw
4 Department of Electronic Science, Fujian Engineering Research Center for Solid-State Lighting, Xiamen University, Xiamen 361005, China
5 HKUST Fok Ying Tung Research Institute, Nansha District, Guangzhou 511458, China
* Correspondence: wutingzhu@xmu.edu.cn (T.W.); hckuo@faculty.nctu.edu.tw (H.-C.K.); Tel.: +886-35712121-31986 (H.-C.K.)

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Abstract: In this study, we present a novel type of package, freeform-designed chip scale package (FDCSP), which has ultra-high light extraction efficiency and bat-wing light field. For the backlight application, mainstream solutions are chip-scale package (CSP) and surface-mount device package (SMD). Comparing with these two mainstream types of package, the light extraction efficiency of CSP, SMD, and FDCSP are 88%, 60%, and 96%, respectively. In addition to ultra-high light extraction efficiency, because of the 160-degree bat-wing light field, FDCSP could provide a thinner and low power consumption mini-LED solution with a smaller number of LEDs than CSP and SMD light source array.

Keywords: chip scale package; freeform design; mini LED; light emitting diode

1. Introduction

For next generation liquid crystal display (LCD) displays, high dynamic range (HDR) is an important feature [1]. To achieve HDR, local dimming is a technique, which can effectively suppress the dark state and greatly enhance the contrast ratio [2–4]. For local dimming technique, segmented light emitting diodes (LEDs) are adopted in the LCD backlight unit, where the local zones can be independently dimmed to match the displayed image contents. For direct lit backlight system with local dimming function, two types of LED packages are widely used. One is traditional surface-mount device (SMD) LED [5,6], the other is chip-scale package (CSP) [7]. For SMD LED, it is the most popular design. Its process is to mount an LED chip in a cavity substrate, and then fill silicone mixed with phosphor into the cavity. This process is very simple and easy to mass production. However, its view angle is limited by the cavity substrate. When we apply SMD LED to a direct lit backlight system, it is necessary to add a secondary lens that can increase the view angle on the top of LED. Thus, the CSP solution, which is to deposit a phosphor layer on the top of Flip chip LED, was proposed to solve this issue these years since CSP has a larger view angle and better light extraction efficiency [8,9].

Recently, because of the excellent contrast performance and wide color gamut potential, the micro-LED with a chip size smaller than 100 µm becomes the mainstream research topic of display technique [10–14]. Though the micro-LED display has huge potential to be the future display, the expensive cost and low yield in the mass transfer process obstruct the popularize progress of micro-LED [15,16]. On the other hand, mini-LED has a larger chip size (100–500 µm) than micro-LED and its fabrication is much easier [17,18]. Thus, mini-LED is an ideal backlight candidate to enable local dimming for LCDs. Considering the cost and performance, the mini-LED solution, which has a lightly larger pitch than micro-LEDs and owns excellent contract performance with the local dimming technique is vigorously developing.

To achieve the most suitable mini-LED solution, we combine the concept of direct lit backlight solution, which has a secondary lens like SMD LED to reshape the light field to the bat-wing type and has high light extraction efficiency like CSP LED. Then, this kind of structure is called freeform-designed chip scale package (FDCSP). This FDCSP type LED arrays could provide both ultra-high light extraction efficiency and ultra-thin direct lit backlight solution for mini-LED applications.

2. Experiment

Figure 1 shows the schematic diagram of three types of mini-LED, which are (a) CSP, (b) SMD, and (c) FDCSP. 100 µm × 100 µm flip chip is used in these three types of packages as their light sources. For CSP mini-LED, a 35 µm thickness and 90% concentration of phosphor layer is deposited on the chip, then a transparent silicone is molded on the top of the phosphor layer. The particle size called D50 and D90 of commercial phosphor is about 15 µm and 25 µm, respectively. D50 is the average of particle size. D90 describes the diameter where 90 % of the distribution has a smaller particle size and 10% has a larger particle size. Based on these values, 35 µm for the phosphor layer is close to the design limitation. Using the phosphor concentration of 90% for both CSP and FDCSP can meet the backlight color temperature criteria, which is 10,000 K. The size of CSP mini-LED is 1.5 mm × 1.5 mm × 0.8 mm. The optimization of thickness of CSP phosphor layer and CSP package referred to the previous work [6]. For SMD mini-LED, chip is mounted in a cavity substrate, and phosphor is evenly distributed in the cavity with concentration 10% to meet the 10,000 K backlight color temperature. For FDCSP mini-LED, a 35 µm thickness and 90% concentration of phosphor layer is deposited on the chip, then a transparent lens with freeform surface design is molded. We analyzed the light source efficiency and illuminance angle by Light Tools™ (Synopsys Inc, Mountain View, CA, USA) for these three kinds of light sources, and then model the module as shown in Figure 2. The size of module architecture is 30 mm × 30 mm. For the light performance of module using CSP, SMD, and FDCSP, MATLAB is used to call the Lighttools API and numerical operations. There are two important parameters to analyze the performance of the module. One is the distance between the light source and the receiving surface. This parameter is called optical distance, "OD". The other is the arrangement of the light source arrays, this parameter called "Pitch". Spot uniformity and energy efficiency of module using three types of packages will be evaluated based on these two parameters, OD and Pitch. These two parameters are very important to the evaluation of the direct-lit backlight system [19–21]. If the OD is smaller, it means that this backlight module is thinner. If the Pitch is larger, it means that less LEDs are used in this module.

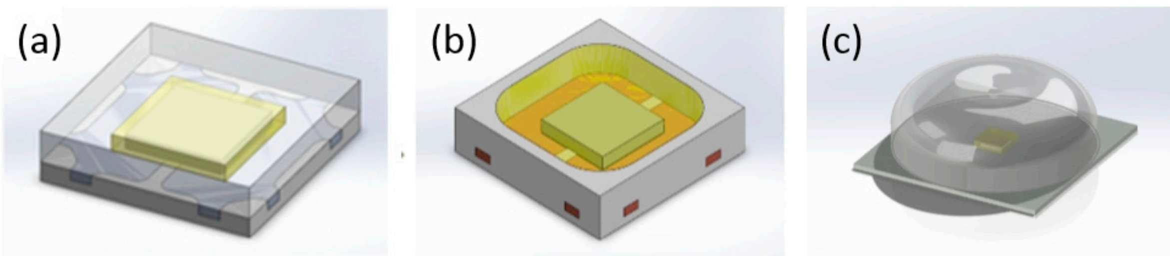

Figure 1. Schematic diagram (**a**) CSP, (**b**) SMD, and (**c**) FDCSP.

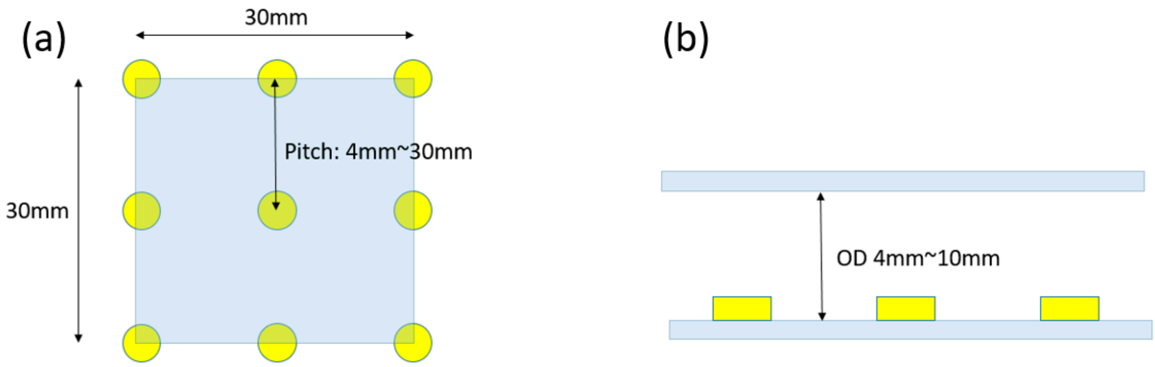

Figure 2. Schematic diagram of (**a**) the Pitch and (**b**) the OD for a backlight module.

3. Result and Discussion

Firstly, we analyze the energy loss and spot characteristics of the light source components. Through Lighttools simulation, Figure 3 records the illumination angles of the three light sources CSP, SMD, and FDCSP, respectively. The CSP source has an illumination angle of 130 degrees and a Gaussian distribution, while the SMD has an illumination angle of 120 degrees, which is also a Gaussian distribution. More specifically, the FDCSP has a 160 degrees bat wing distribution pattern.

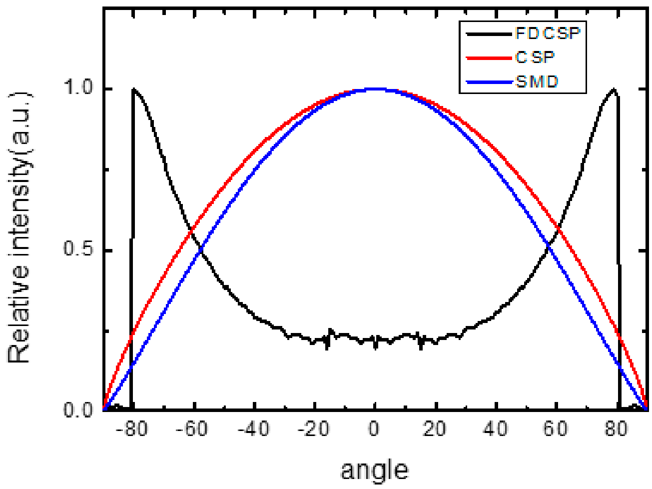

Figure 3. View angle of CSP, SMD, and FDCSP.

Figure 4 shows the ray tracing profile simulated by Lighttools. The system efficiency calculation results of CSP, SMD, and FDCSP are 88%, 60%, and 96%, respectively. From Figure 4, it can be clearly observed that the system efficiency is proportional to the number of rays out of the surface. Due to the design of the free-form surface, the FDCSP has a low proportion of the total beam reflection, resulting in minimal energy loss. As SMD is only a one-sided illumination and has no curved surface characteristics, the number of rays that the beam is reflected and total internal reflection (TIR) in the package is very large, thus causing a large amount of energy loss.

Then, the CSP, SMD, and FDCSP light sources are analyzed in the module, respectively. The module parameter "OD" is 4 mm to 10 mm, the step is 1 mm; and the module parameter "Pitch" is 30 mm, 15 mm, 10 mm, and 7.5 mm, respectively. Figures 5–7 show the module operation results of CSP, SMD, and FDCSP, respectively. The file name format of each thumbnail in the picture is "Pitch-OD-Uniformity-Intensity". For example, the name "7.5-4-87%-912259" of picture means that the pitch of LED array is 7.5 mm, OD is 4 mm, and backlight module uniformity is 87%, and the intensity is 912,259 nits. The uniformity is defined, as shown in Equation (1).

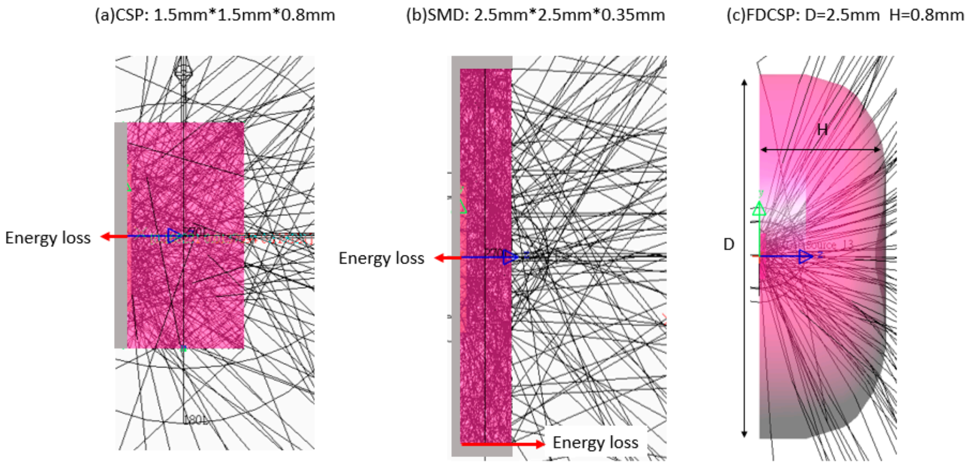

Figure 4. Light tracing profile of (**a**) CSP, (**b**) SMD, and (**c**) FDCSP.

In addition to uniformity, in order to properly express the ability of the program, this paper defines the ratio of Pitch to OD as an evaluation index of the program ability, the "solution factor", S. A detailed mathematical definition is defined as Equation (2).

$$Solution\ factor\ S\ (\text{Minimum uniformity, minimum intensity}) = \frac{PITCH}{OD} \tag{2}$$

Taking S (85%, 100%) = 2 for example, it means that the minimum uniformity and minimum intensity of backlight module are 85 % and 100 %, respectively, and the Pitch is twice the value of OD. If the Pitch is large, it means that a smaller number of LEDs are used in the module, leading to the low cost and power consumption for the backlight system. If the OD is small, it means that the backlight module is thin. Therefore, a backlight module with the larger solution factor will be more cost-effective and thinner, and solution factor can be a quantitative indicator for the performance of direct lit backlight system using mini-LED.

$$Uniformity = \frac{\text{minimum pixel value of image}}{\text{maximum pixel value of image}} \times 100\% \tag{1}$$

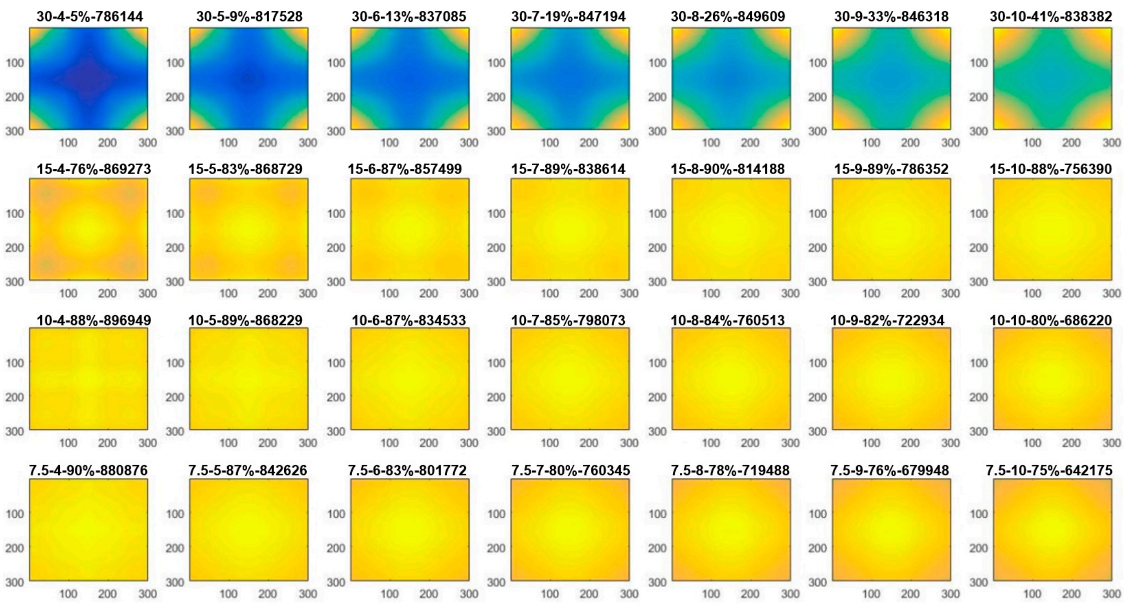

Figure 5. Array analysis of CSP.

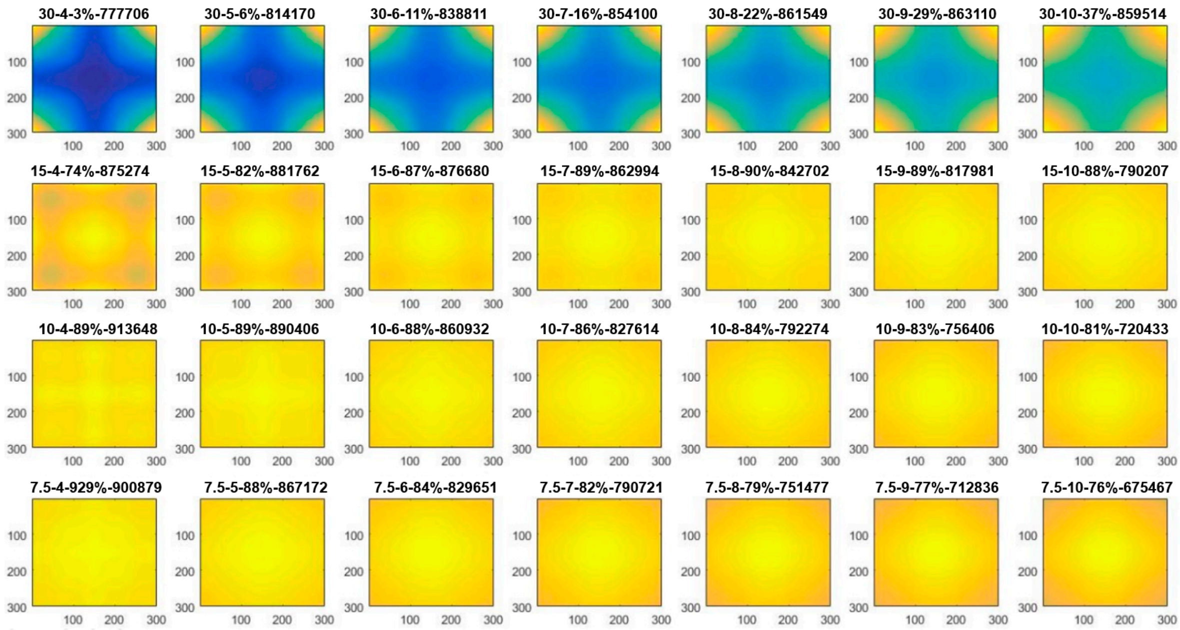

Figure 6. Array analysis of SMD.

Figure 5 is an image series of an array of CSPs. Qualitatively, when Pitch = 30 mm, since the illumination type of the light source is the Gaussian distribution, the light pattern cannot be effectively opened in the interval of OD = 4 mm to 10 mm. Therefore, the images all show obvious cross-dark characteristics (blue area). As shown in Figure 6, SMD also has the same characteristics, while FDCSP has no obvious cross-dark band when OD = 8 mm or more, such as Figure 7. Based on the above results, the bat wing light type clearly has the ability to provide large Pitch solution on the display plane. On the other hand, as can be seen from Figures 5–7, the image uniformity increases significantly as the Pitch shrinks and the OD increases until the OD is large enough or the Pitch is small enough to achieve saturation. As shown in Figures 5–7, the uniformity of the image has not changed significantly when OD > 6 mm or Pitch < 7.5 mm. This parameter interval is the saturation interval. In addition, from the value of Intensity, it can be seen that Intensity basically decreases with OD increasing.

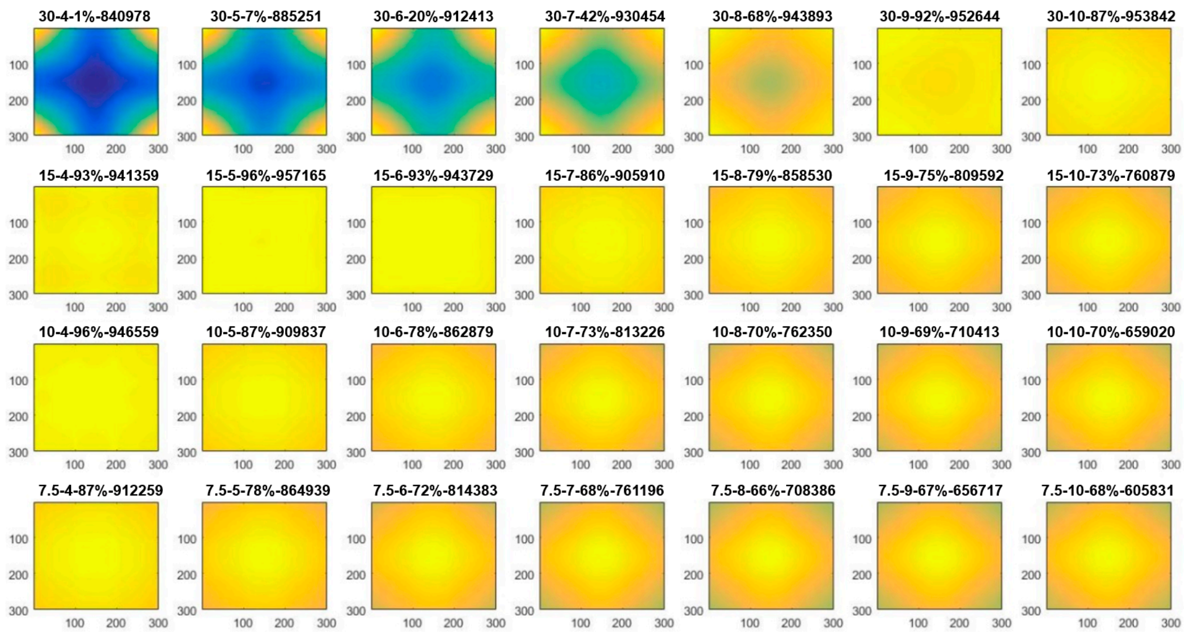

Figure 7. Array analysis of FDCSP.

In order to further discuss the optical phenomenon in the unsaturated interval, we take the parameters of each image and normalize the simulation results of each condition based on the Intensity of CSP at OD = 4 mm and Pitch = 30 mm, as shown in Table 1. First of all, we can clearly observe that the module intensity of FDCSP scheme is much higher than that of CSP and SMD because the light extraction efficiency of FDCSP is better than CSP and SMD. Therefore, the overall efficiency of the intensity is more than 130%. In contrast, the SMD is not efficient due to the low package efficiency of initial light source. The normalized intensity value is only about 70%. Then, in order to further distinguish the capabilities of each light source scheme, this study is aimed at S (85%, 60%), S (85%, 70%), S (85%, 100%), and S (85%, 110%) to draw a strategy map with different conditions. Figure 8 demonstrates the strategy map of S (85%, 60%), S (85%, 70%), S (85%, 100%), and S (85%, 110%), respectively. Due to poor efficiency, the SMD series has no solution at S (85%, 100%) and S (85%, 110%). Additionally, the CSP only has smaller OD solutions at S (85%, 110%) as the threshold of intensity increases. It is worth mentioning that the FDCSP solution has not changed significantly under any conditions.

Table 1. Module modeling result. The numbers in the frame means that the uniformity of modulus is over 85%.

Pitch (mm)	OD (mm)	Uniformity-CSP (%)	Uniformity-SMD (%)	Uniformity-FDCSP (%)	Intensity-CSP (a.u.)	Intensity-SMD (a.u.)	Intensity-FDCSP (a.u.)
30	4	5	3	1	100%	67%	117%
30	5	9	6	7	104%	71%	123%
30	6	13	11	20	106%	73%	127%
30	7	19	16	42	108%	74%	129%
30	8	26	22	68	108%	75%	131%
30	9	33	29	92	108%	75%	132%
30	10	41	37	87	107%	75%	132%
15	4	76	74	93	111%	76%	131%
15	5	83	82	96	111%	76%	133%
15	6	87	87	93	109%	76%	131%
15	7	89	89	86	107%	75%	126%
15	8	90	90	79	104%	73%	119%
15	9	89	89	75	100%	71%	112%
15	10	88	88	73	96%	69%	106%
10	4	88	89	96	114%	79%	131%
10	5	89	89	87	110%	77%	126%
10	6	87	88	78	106%	75%	120%
10	7	85	86	73	102%	72%	113%
10	8	84	84	70	97%	69%	106%
10	9	82	83	69	92%	66%	99%
10	10	80	81	70	87%	62%	91%
7.5	4	90	92	87	112%	78%	127%
7.5	5	87	88	78	107%	75%	120%
7.5	6	83	84	72	102%	72%	113%
7.5	7	80	82	68	97%	69%	106%
7.5	8	78	79	66	92%	65%	98%
7.5	9	76	77	67	86%	62%	91%
7.5	10	75	76	68	82%	59%	84%

In addition, from the strategy map, the ability of solution can be evaluated by the value of the "solution factor". FDCSP's solution factor S can reach up to 3.75, while CSP and SMD have a maximum solution factor S of 2.5. This means that FDCSP mini-LED can provide a larger pitch solution under the same OD conditions. Combining the above results, with a high solution factor value and high light extraction efficiency, FDCSP can be a highly efficient light source for ultra-thin mini-LED display applications.

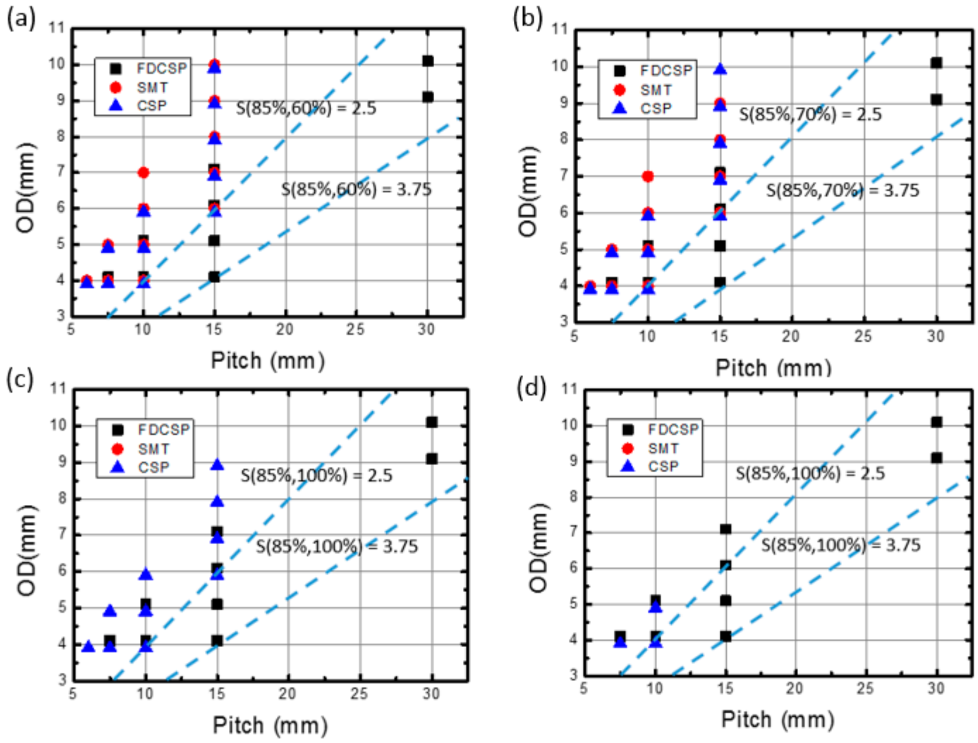

Figure 8. The strategy map for (**a**) uniformity > 85%, Intensity > 60%, (**b**) uniformity > 85%, Intensity > 70%, (**c**) uniformity > 85%, Intensity > 100%, and (**d**) uniformity > 85%, Intensity > 110%.

Due to the direct refracting light characteristics, the FDCSP light source has higher light extraction efficiency than the CSP and SMD light sources. According to Table 2, FDCSP, CSP, and SMD light sources have a light extraction efficiency of 96%, 88%, and 60%, respectively. In addition, due to the bat wing light type, FDCSP has a higher solution factor on the display module, and can provide S (85%, 110%) = 3.75, with a larger Pitch and high intensity scheme under the condition of OD = 4 mm. On the contrary, since both the light types of CSP and SMD are Gaussian-distributed, the solution factor is, at most, 2.5. Combining the above characteristics, FDCSP provides an excellent solution for ultra-thin mini-LED due to its high efficiency and high solution factor.

Table 2. Comparison of different light source.

	CSP	**SMD**	**FDCSP**
PKG Efficiency	88%	60%	96%
Angular	130° Gaussian distribution	120° Gaussian distribution	160° Bat wing distribution
Array Efficiency @OD4 Pitch10mm	111%	76%	131%
Solution Factor S S (85%, 60%)	1.5 < S (85%, 60%) < 2.5 Max intensity: 112% Max OD = 10	1.4 < S (85%, 60%) < 2.5 Max intensity: 78% Max OD = 10	2.1 < S (85%, 60%) <3.75 Max intensity: 131% Max OD = 10
Solution Factor S S (85%, 70%)	1.5 < S (85%, 70%) < 2.5 Max intensity: 112% Max OD = 10	1.4 < S (85%, 70%) <2.5 Max intensity: 78% Max OD = 9	2.1 < S (85%, 70%) <3.75 Intensity: 131% Max OD = 10
Solution Factor S S (85%, 100%)	1.5 < S (85%, 100%) < 2.5 Max intensity: 112% Max OD = 9	NA	2.1 < S (85%, 100%) <3.75 Intensity: 131% Max OD = 10
Solution Factor S S (85%, 110%)	1.5 < S (85%, 110%) < 2.5 Max intensity: 112% Max OD = 5	NA	2.1 < S (85%, 110%) <3.75 Intensity: 131% Max OD = 10

4. Conclusions

In this study, we develop a new package type FDCSP and simulate its performance by adjusting two parameters of the Pitch and the OD. Compared to the traditional CSP and SMD, FDCSP has a better light extraction efficiency (96%). In addition, the bat-wing light shape makes FDCSP more suitable for mini-LED display applications with a higher solution factor. For the realistic requirement in display applications, we expect the mini-LED backlight has local dimming function and slim thickness, with lower cost and low power consumption characteristics. Therefore, this FDCSP type of light source array could provide both ultra-high light extraction efficiency and ultra-thin direct type backlight solution for mini-LED application. FDCSP can be regarded as a model for practitioners who desire to improve the quality of mini-LED displays.

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Conflicts of Interest: The authors declare that there are no conflicts of interest related to this article.

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