Design of a backlight module with a freeform surface by applying the Taguchi method

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A novel structure, called a "freeform surface," is integrated into a direct type light-emitting diode backlight. By applying the Taguchi method, the performance of this backlight is optimized. The Taguchi experiments are configured in $L_9(3^4)$ orthogonal arrays and are simulated via LightTool analysis software. After that, the influence of the design parameters on the luminance and uniformity are separately evaluated by analysis of variance (ANOVA). Next, the parameters are optimized, and a new backlight structure with desirable performance is designed at last. LightTool simulation shows that this new type of backlight is just 15 mm thick and has 310.3 nits luminance and 83.5% uniformity.

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Recently, we have witnessed the rapid development of the panel display, and the demand for slim and large-scale displays is growing quickly[1]. The large-size panel display usually adopts the direct type backlight modules with a 20–50 mm thickness[2]. The direct type backlight module has light-emitting diode (LED) sources positioned directly onto the bottom of the backlight[3]. In order to achieve a uniform lighting effect, a sufficient light mixing distance must be preserved, which conflicts with the trend of a slim panel display. Therefore, a new backlight module structure with a freeform surface is proposed.

In this Letter, a backlight module with a freeform surface is designed and optimized by using the Taguchi method[1,4] with its experiments conducted through LightTool analysis software[5]. The simulation shows that the new type of optimized backlight module yields a uniformity of 83.5%, a luminance of 310.3 nits, and a thickness of just 15 mm.

Therefore, the freeform surface is integrated into the housing to redistribute the light of the LEDs, as shown in Fig. 2. By increasing the radian of the freeform surface, the optical path is longer, which translates into a longer light mixing distance. In addition, a microstructure is used to change the direction of the horizontal light in order to enhance the light-extraction efficiency of the backlight.

As shown in Fig. 2, the freeform surface can be described as a piecewise function. The normal plane, where the LEDs are mounted, is described as $\vec{n} = (x_0, y_0, \tan\,\theta_0\sqrt{x_0^2 + y_0^2})$. Every point (x, y, z) on the plane is defined as Function 1. The ordered parts of the freeform surface have no definite shape. Transformed to spherical polar coordinates, the freeform surface is described as Function 2:

$$x_0(x - x_0) + y_0(y - y_0) + \tan\,\theta_0\sqrt{x_0^2 + y_0^2}(z - z_0) = 0, \tag{1}$$

$$\begin{cases} R, \theta\epsilon(0, \theta_1)\cup(\theta_2, \pi), \varphi\epsilon(0, \varphi_1)\cup(\varphi_2, \pi) \\ x_0\left(\dfrac{R}{\cos\,\theta\,\cos\,\varphi} - x_0\right) + y_0\left(\dfrac{R}{\cos\,\theta\,\sin\,\varphi} - y_0\right) + \tan\,\theta_0\sqrt{x_0^2 + y_0^2}\left(\dfrac{R}{\sin\,\theta} - z_0\right) = 0, \theta \in (\theta_1, \theta_2), \varphi\epsilon(\varphi_1, \varphi_2) \end{cases}. \tag{2}$$

The simplified module of a traditional direct type LED backlight is shown in Fig. 1[6]. It consists of a metal (aluminum) housing containing some LED bars on the bottom. Directly above the LED bars are a diffuser plate and brightness enhancement films (BEFs) that increase color mixing and enhance brightness. When the light mixing distance is short, the direct type backlight cannot satisfy uniformity and cannot avoid leading the spot issue[6–8].

Before applying the Taguchi method to design the experiment, the characters of backlight performance and the rules to measure them need to be defined.

In this Letter, luminance and uniformity are the characters of the backlight's performance[9–12] and are supplied by the client or defined by ourselves. According to the test standard of a panel display[13], a TV with a uniformity >80% can be considered an acceptable product. In

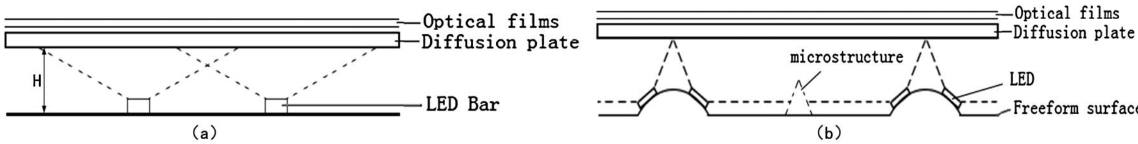

Fig. 1. Direct type LED backlight module (a) traditional structure; (b) new structure with a freeform surface.

addition, the luminance of the LCD TV is usually 300–350 nits[14]. Because the transmittance of the LCD panel is about 4%, the backlight should provide a 7500–8570 nits luminance.

In order to produce a 7500–8750 nits luminance, an estimated 240 LEDs are needed using the formula below[15], where the LED is a Lumiled LXHL-PM01 with $\Phi_{\mathrm{LED}} = 53$ lm/W, and the backlight module is 30 in. with a 560 mm × 420 mm cavity:

$$\mathrm{N} \approx \frac{A_{\mathrm{backlight}} L_{\mathrm{peak}}}{T_{\mathrm{LCD}} E_{\mathrm{cavity}} G_0 \Phi_{\mathrm{LED}}} \int_0^{2\pi} \int_0^{\pi/2} f(\theta, \varphi) \sin\theta \cos\theta \mathrm{d}\theta \mathrm{d}\varphi, \tag{3}$$

where $A_{\mathrm{backlight}}$ is the area of the backlight module, E_{cavity} is the transmission efficiency of the cavity with the diffuser plate (output luminous flux/LED-array luminous flux), $G_o = G\,(\theta = 0, \varphi = 0)$ is the overall axial gain of the stack of luminance enhancement plates, T_{LCD} is the transmission efficiency of the LCD panel which usually is ~4%, L_{peak} is the peak screen luminance, and Φ_{LED} is the luminous flux of the LED.

In this Letter, the LEDs are placed into a triangular, square, or hexagonal array, and the angle of the LEDs is defined as 0°, 50°, or 90°, with the location of the microstructure in the center of the LED array. The shape of this structure can be defined as no, cone, or cylinder with a 12 mm height. Directly above the LED array is a bulk diffuser, as shown in Fig. 2.

After understanding the structure well, control factors should be discussed. The mounting degree of the LEDs mainly influences their direction. The smaller the mounting degree is, the more light goes in the vertical direction, and the easier a light spot issue is created. It is obvious that the light mixing distance is an important control factor for brightness and uniformity. The shorter the light mixing distance is, the more light can be extracted from the backlight, while it is easier to get the spot issue. Besides, as the LED is a Lambertian source, a different arrangement of the LEDs can provide a different lighting effect, which is also controlled by the shape of the microstructure. Therefore, the control factors that affect the performance of the backlight can be determined as: (1) the shape of the microstructure, (2) the light mixing distance, (3) the arrangement of LEDs, and (4) the mounting angle of the LEDs. The levels of the control factors are chosen in an appropriate range based on the current form of the backlight, as shown in Table 1. After picking the factors and levels, the experiments that are assembled in the orthogonal array as shown in Table 2 are simulated through LightTool software.

Table 2 also includes the uniformity, the luminance of the backlight, and the S/N ratio, which quantified the quality characters. In these experiments, the luminance and uniformity are expected to be larger and thus better. Therefore, the S/N ratio of the luminance or the uniformity can be expressed as

$$\eta = -10 \log \frac{\sum_{i=1}^{n} \frac{1}{y_i^2}}{n}, \tag{4}$$

where y_i denotes the value of the uniformity or luminance associated with the ith test, i is the index number of the

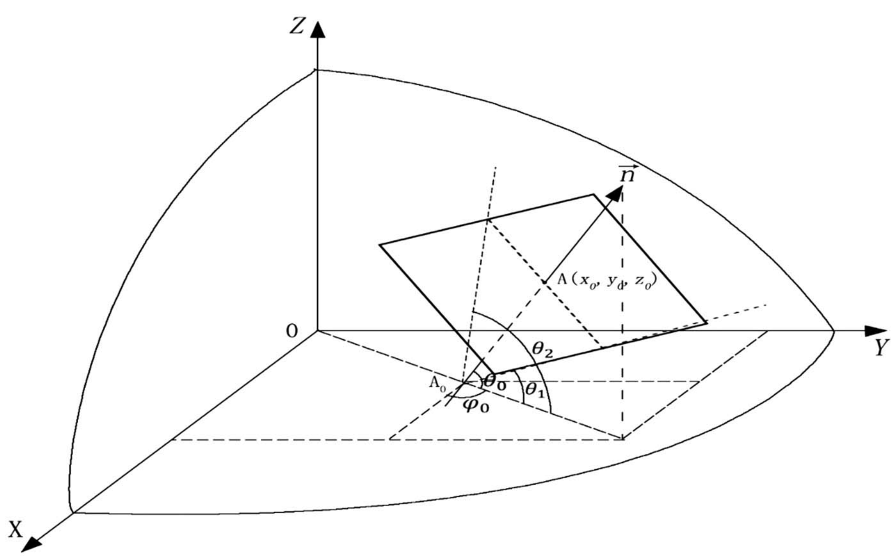

Fig. 2. Mathematical model of the freeform surface.

Table 1. Control Factors and Levels for Backlight Module Quality

Symbol	Parameter Description	Number of Levels	Level 1	Level 2	Level 3
A	Microstructure	3	no	Cone	Cylinder
B	Light mixing distance	3	38	30	25
C	Arrangement of LEDs	3	Triangle	Square	Hexagon
D	Mounting angle of LEDs	3	0°	50°	90°

Table 2. Experiments Designed with a $L_9(3^4)$ Orthogonal Array

Experiment Number	A	B	C	D	Uniformity	Luminance (nits)	S/N of Uniformity	S/N of Luminance
1	1	1	1	1	55.64	6890.07	34.91	76.76
2	1	2	2	2	66.86	7181.67	36.50	77.12
3	1	3	3	3	68.50	7322.62	36.71	77.29
4	2	1	2	3	61.96	6881.79	35.84	76.75
5	2	2	3	1	67.94	7536.03	36.64	77.54
6	2	3	1	2	63.59	7204.62	36.07	77.15
7	3	1	3	2	65.93	7127.34	36.38	77.06
8	3	2	1	3	64.00	7139.51	36.12	77.07
9	3	3	2	1	66.44	7522.38	36.45	77.53

performed test, and n is the total number of data points per trial.

The S/N ratio of the different levels can be shown clearly from Fig. 3. The most uniform performance can be provided with the parameter settings A3-B2-C3-D2, while the parameter settings A3-B3-C3-D1 present the brightest lighting effect among all the parameter combinations.

As shown in Fig. 3, factor B yields a bigger influence on increasing luminance than uniformity. Therefore, B3 is chosen as the optimal parameter because it effectively enhances the luminance while having little influence on the uniformity. Also, factor D has little influence on the backlight luminance. Taking luminance and uniformity into consideration, parameter D2 is chosen to ensure a highly uniform performance. Finally, based on Fig. 3 and the conclusion as previously discussed, the parameter settings are defined as A3-B3-C3-D2, and the simulation result is shown that the nine-point uniformity of the backlight is 70.67%, the highest in the experiments, while the average luminance is 7330.27 nits, close to the highest luminance (7522.38 nits).

These results are because we tend to improve the uniformity rather than luminance when choosing factor D. However, the performance of the backlight module with the optimal parameters still cannot reach the target. Therefore, the parameters must be further adjusted to meet the demand.

The analysis of variance (ANOVA) technique is utilized to estimate the cause-and-effect relationship between the design factors and performance. The significance of the factors is calculated and known as the "important level." The important level can be defined as ρ

$$\rho = \frac{SS_d}{SS_t}, \tag{5}$$

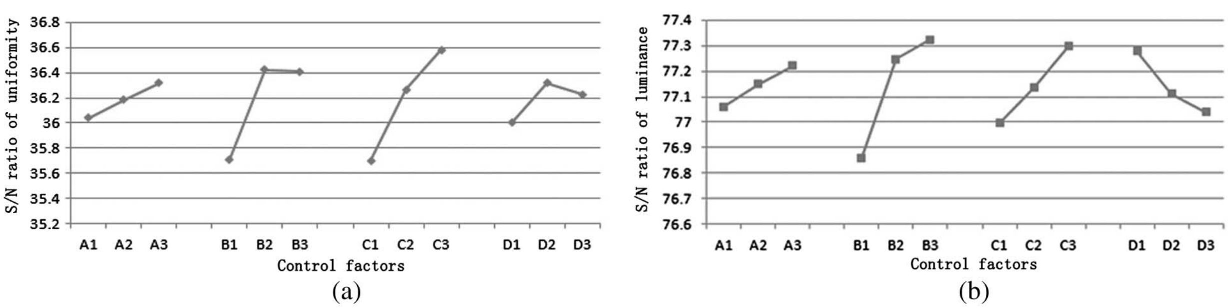

Fig. 3. S/N ratios of (a) uniformity and (b) luminance at different levels.

Table 3. ANOVA Results of Uniformity and Luminance

	Factor	A	B	C	D
Uniformity	SS_d	0.11	1.00	1.19	0.16
	Contribution (%)	4.65	40.46	48.36	6.53
Luminance	SS_d	0.04	0.37	0.14	0.09
	Contribution (%)	5.98	58.53	21.46	14.03

$$SS_t = SS_d + SS_e, \tag{6}$$

where SS_d is the sum of the squared deviations, and SS_e is the sum of the squared error. (Note that SS_e is approximated as 0 since the simulations are repeatable.) The total sum of the squared deviation SS_t from the total mean S/N ratio η_n can be expressed as[4]

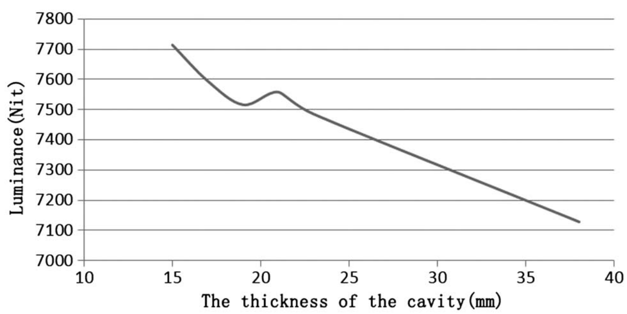

Fig. 4. Relationship between the luminance and the thickness of the cavity.

$$SS_t = SS_d = \sum_{i=1}^{n_i} (\eta_i - \eta_n)^2, \tag{7}$$

where n_i is the number of experiments in the orthogonal array, and η_i means the S/N ratio of the ith experiment.

Table 3 summarizes the ANOVA results for uniformity and luminance. The results show that the arrangement of the LEDs (factor C, 48.36%) has the most influence on the uniformity, followed by the light mixing distance (factor B, 40.46%). In addition, the thickness of the cavity (factor B, 58.53%) is the main influence on the luminance among all the factors. It is evident that factor A affects both uniformity and luminance the least. In order to reduce the cost and time of the manufacturing process, the microstructure does not need to be produced. On the contrary, the mounting angle of a LED has little influence on uniformity and luminance, but it allows for the possibility of a slimmer backlight because it ensures a long-enough light mixing distance and prevents the spot issue.

Uniformity is ruled by the thickness of the cavity and the arrangement of the LEDs, while luminance is just determined by the thickness of the cavity. Therefore, the luminance of the backlight module is first improved by shortening the thickness of the cavity. As shown in Fig. 4, the luminance is improving while the thickness of the cavity is decreasing. When the thickness is <23 mm, the luminance of the backlight reaches the goal. Following the trend toward slim displays, the thickness of the backlight is defined as 15 mm.

After the luminance is bright enough for the demand, uniformity is improved by adjusting the arrangement of the LEDs. The final optimal backlight module is shown in Fig. 5. This newly designed product not only is suitable for

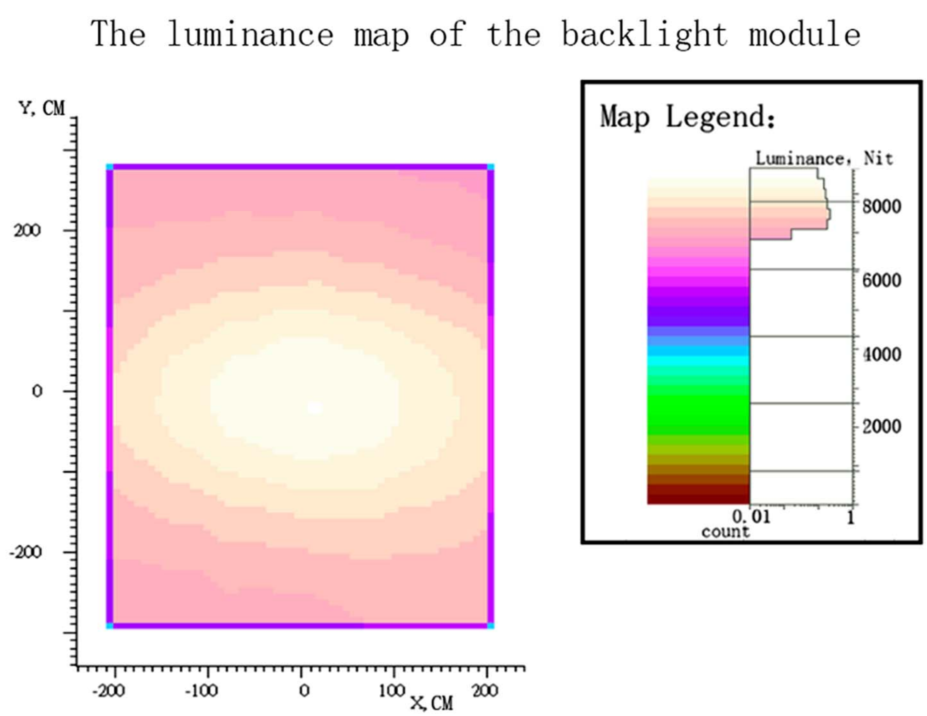

Fig. 5. Luminance map of the backlight module with optimized parameters.

Table 4. Luminance of the Backlight Module with Optimized Parameters in a Nine-Point Test

y/x	−165	0	165
223	7318.554	7388.185	7229.667
0	8062.3365	8655.6785	8142.987
−223	7299.869	7460.407	7502.769

the demand of a slim direct type backlight, but also has an excellent performance with 83.5% nine-point-uniformity and 7755 nits average luminance as shown in Table 4.

A new backlight module with a freeform surface is proposed. By using the Taguchi method and LightTool software, the optimal design parameters A3-B3-C3-D2 are easily achieved. After that, the ANOVA technique is utilized to analyze the contribution of the factors to performance. The result shows that the arrangement of LEDs has the biggest influence on the uniformity (48.36%), followed by the thickness of the cavity (40.46%), while the thickness of the cavity is the main influence on the luminance (58.53%) among the factors. Finally, the backlight with the desired performance is produced with further design. Overall, designing a backlight module with a freeform surface and applying the Taguchi method cannot only shorten the design cycle, but also provide a new solution to design a slimmer, direct type backlight module with desirable performance.

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