Microsyst Technol (2013) 19:1669–1678
DOI 10.1007/s00542-013-1877-x

TECHNICAL PAPER

Optimizing angular placements of the LEDs in a LCD backlight module for maximizing optical efficiency

Paul C.-P. Chao · Che-Hung Tsai · Jiun-De Li · Wei-Dar Chen

Received: 31 October 2012 / Accepted: 1 June 2013 / Published online: 26 June 2013

Abstract This study aims to optimize angular placements of the LEDs with novel cone-shaped caps for achieving high optical efficiency in an ultra-thin, directly-lit RGB LED backlight unit (BLU) for large-sized LCD-TVs. This novel lens cap is used as a diffuser with the purpose to gain higher efficiency and provide satisfactory uniformity over a display panel. To this aim, the outer surface of the novel lens is coated with aluminum for mirroring effects to reflect most of the LED emitted light horizontally and then reflect the light at the BLU boundaries, finally to the output plane. Since the emitted white light from LEDs result from color-mixing of three individual RGB chips in a LED package, the addition of the LED cap however deteriorates the aforementioned expected color mixing. The optimal design on angular placements of LEDs presented in this study for satisfactory color-mixing and emission uniformity is achieved by necessary optics simulations via TracePro, followed by utilizing an intelligent numerical optimization technique, genetic algorithm (GA). The design parameters for GA optimization are different combinations of LED placement angles in a backlight module. Favorable color balance is shown achievable in terms of high low color difference resulted. Finally, experiments are conducted, which successfully validate the expected performance of color balance and emission uniformity for a novel cone-shaped LED lens with optimized angular placements in a large-area backlight module.

P. C.-P. Chao (✉) · C.-H. Tsai · W.-D. Chen
Department of Electrical Engineering,
National Chiao Tung University, Hsinchu 300, Taiwan
e-mail: pchao@mail.nctu.edu.tw

P. C.-P. Chao
Department of Imaging and Biophotonics,
National Chiao Tung University, Tainan 711, Taiwan

J.-D. Li
Department of Mechanical Engineering,
Chung Yuan Christian University, Chung Li 320, Taiwan

1 Introduction

LCD-TVs with RGB LEDs as light sources are widely applied in market. Several previous research works focused on achieving higher color gamut for high performance (Martynov et al. 2003; Käläntär and Okada 2004; Schubert 2006; Chao et al. 2008; Huang et al. 2011; Lin et al. 2019). Recently, a newly secondary optical lens module have been designed to increase the luminance and uniformity (Chang et al. 2012). Hao et al. (2011) proposed a method to achieve uniformity of illuminance for large scale LED BLU. On the other hand, with the manufacturing techniques for LEDs developed in a fast speed, high power LEDs are legitimate candidates for large-size directly-lit LCD-TV BLUs with the advantages that only limited number of high-power LEDs are needed to provide required brightness. However, with fewer high-power LEDs used in the BLU as illustrated by Fig. 1a, brightness uniformity and high efficiency cannot be achieved by using conventional diffuser plates and/or sheets, which are originally designed for the side-emission type of BLUs, which requires light guides to achieve required uniformity. The application of these conventional diffuser plates or sheets for high-power LEDs in the directly-lit BLU would, however, lead to thicker thickness and low light utilization. To solve the problems, the past works presented in (Folkerts 2004) proposed a side-emitting lens cap for LEDs in the BLU. This proposed lens, nonetheless, requires the light emitted from the LEDs RGB chips to be transmitted through the lens polymer material before side emission occurs; in results, a substantial amount of light energy is consumed, leading to low light utilization.

This study proposes a novel cone-shaped optical lens cap, as shown in Fig. 2, to be placed on the top of the RGB LED module, as illustrated in Fig. 1b. This is aimed to increase light utilization. By coating aluminum to the outside surface of the cone for mirroring effects to reflect most part of LED emitted light to side directions, the emitted light is then reflected by the white reflectors of the cavity, and finally being able to reach the output surface of the BLU without passing through the lens material. In this way, most of the emitted light energy from LEDs can be well mixed through multiple reflections before reaching the output plane of the BLU. In results, as compared to the approach presented by (Folkerts 2004), higher light utilization is achieved. From another point of view, the designed cone-shaped lens cap plays the role of a diffuser, a low light-efficiency component in BLU, with the aim to gain higher efficiency and simultaneously provide satisfactory uniformity of light distribution. In this way, possible bright spots caused by limited number of high-power LED on the output plane of the BLU can be avoided and then lead to an increased uniformity. The preliminary applicability of this novel lens was presented in (Chao et al. 2006, 2007; Chiu et al. 2007), but they were limited to single-color LEDs in a normally thick BLU.

This study presents a complete development of the lens cap and the accompanying BLU, along with the optimization of LED placement spacing and angles to achieve satisfactory uniformity and color balance (West et al. 2003; Moreno et al. 2005; Malacara 2002; Ries et al. 2003), respectively, eventually toward an ultra-thin BLU. The angular placements of LEDs are particularly optimized since the color-mixing out of a single capped LED is deteriorated since different locations of individual RGB chips in the LED relative to the novel lens may cause a non-axisymmetric distribution of light densities for RGB, leading to less satisfactory color-mixing. The optimization on LED placement angles is accomplished by the genetic algorithm (GA). Finally, the simulated and experimental data were conducted to show the increasing light efficiency of the ultra-thin directly-lit LED BLU by optimal placement spacing and angles. Note that this study are the first one employing the numerical technique of GA to account for a large number of design variables of all different LED placement angles for successfully deriving optimized design and then validated by experiments.

2 Design of the novel cone-shaped lens and an ultra-thin LED backlight module

A design process of the novel lens cap is proposed in this section, which starts with choosing applicable LEDs for the ultra-thin LED BLU. The chosen LED is, as shown in Fig. 3, the EverLight-6123, which has three individual RGB chips in one package. This LED can provide high color gamut lighting and satisfactory white color temperature. In the next stage of design, the critical dimensions of the cone-shaped novel lens cap as shown in Fig. 2 are determined according to the dimensions of the LED, which includes the cone angle of the lens, the diameter of the top circular surface and the bottom one, as shown in Fig. 2c. These critical dimensions affect significantly the emissive intensity profiles of the assembled lens and LED.

Having designed the proposed novel lens, the optical simulation on a large-sized BLU equipped with LEDs is

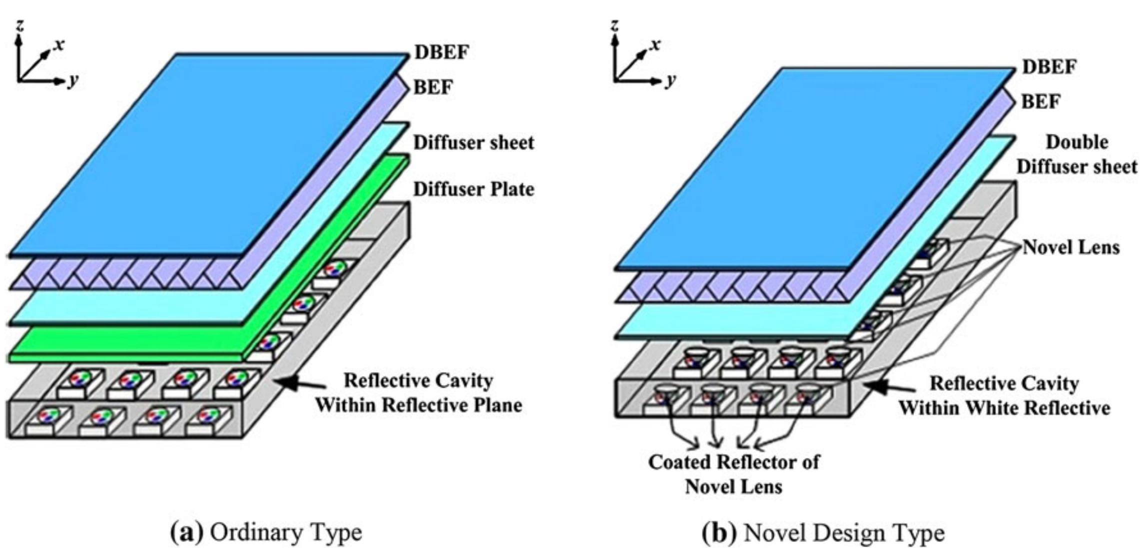


Fig. 1 Illustration of directly-lit LED backlight units: **a** an ordinary LED BLU; **b** the BLU with the proposed novel *cone-shaped* lenses on LEDs

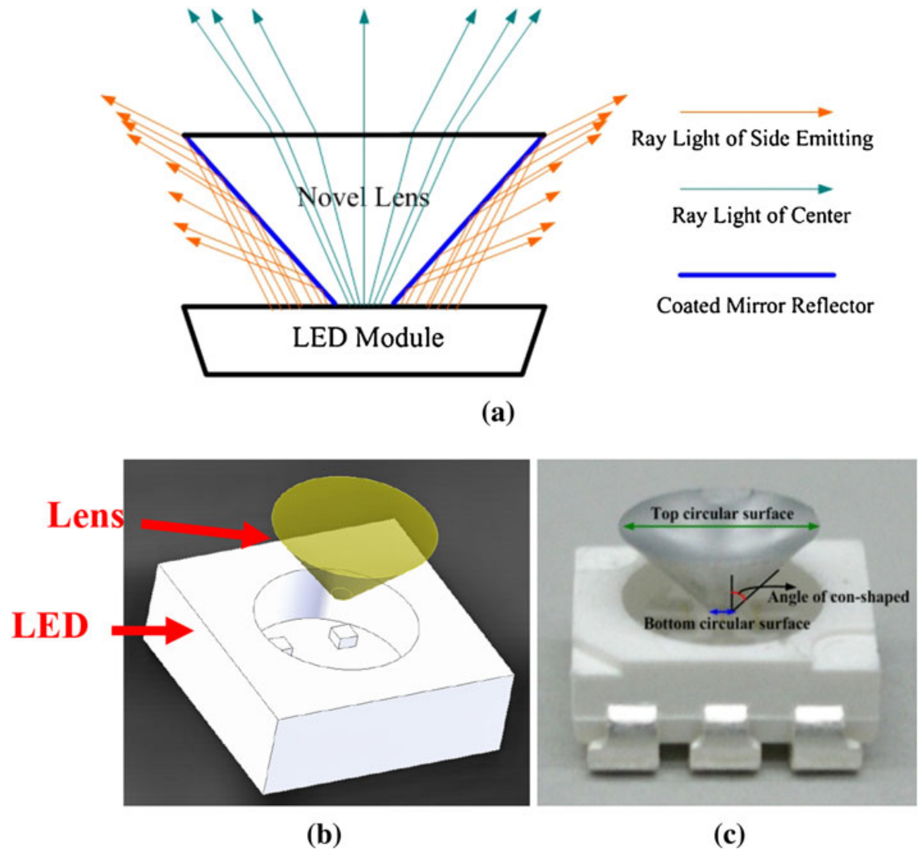


Fig. 2 **a** Optic schematic of LED with the novel *cone-shaped* lens. **b** *Top view* of the LED with the novel *cone-shaped* lens, **c** photograph of the LED module with the novel *cone-shaped* lens

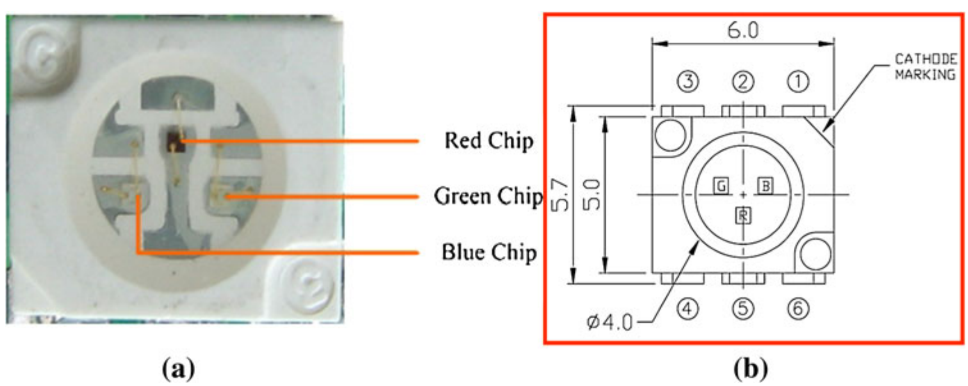


Fig. 3 **a** Photograph of Everlight LED 6123, **b** dimensions of Everlight LED 6123

conducted to design an ultra-thin BLU. The commercial software, TracePro, is applied for preliminary validation on the performance of the BLU. In other to ensure the correctness of the simulation, the settings on varied properties and dimensions of each optical film must be completed and accurate. First, the commercial software TracePro was used for optics simulations. A prototype I BLU with the size of 37 mm × 37 mm is constructed, while another prototype II BLU with a size of 55 mm × 55 mm. Both have thickness of 20 mm, as shown in Fig. 4, and constructed to validate the optical settings for all components and finally verify the brightness predicted by TracePro simulation and design performance.

3 Searching optimal LED angles via GA

The design objective is to search for the optimal angular placement pattern of LEDs. It should be noted first that different locations of individual RGB chips in the LED relative to the novel lens may cause a non-axisymmetric distribution of light densities for RGB, leading to less satisfactory color-mixing. To solve this problem, the LED angles are varied to effectively reach required uniformity and color balancing. In this section, there are two small sizes of the backlight module for studying four and eight optimal angle placements, which are in sizes of 37 mm × 37 mm with four LEDs and the

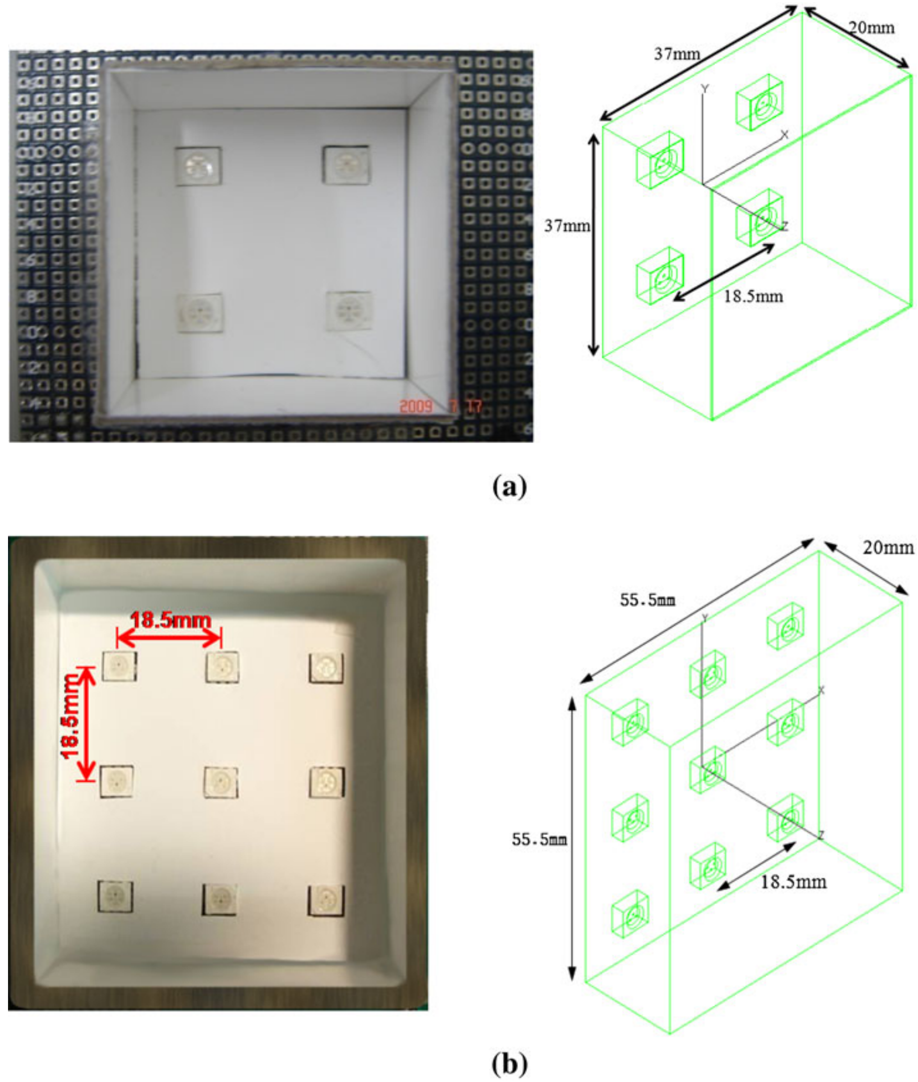


Fig. 4 Photograph of prototype **a** 37 mm × 37 mm BLU module; **b** 55 mm × 55 mm BLU module

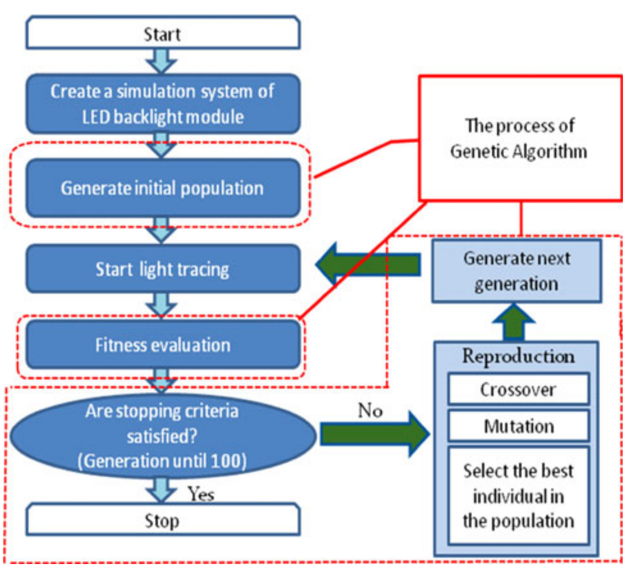


Fig. 5 A flowchart of GA optimization on angular placement pattern of LEDs

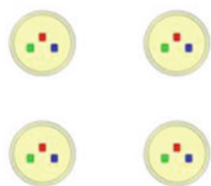
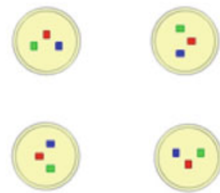
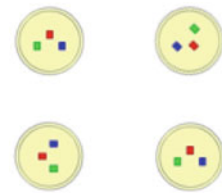
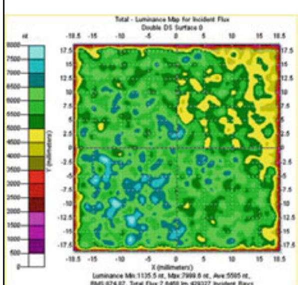
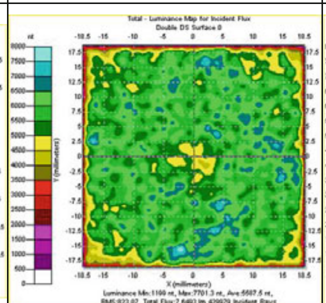
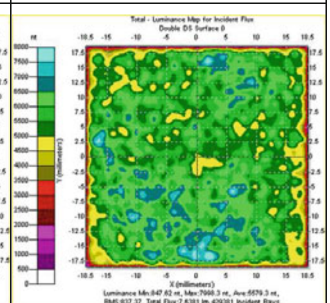
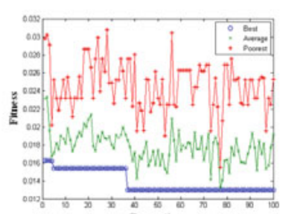
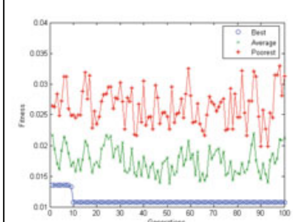
Table 1 The parameter of GA setting

LED	Four LED	Four LED	Nine LED	Nine LED
Angular placement	Four angle placement	Eight angle placement	Four angle placement	Eight angle placement
Generation	100	100	100	100
Population size	40	60	80	100
Length of chromosome	2 bit	3 bit	2 bit	3 bit
Crossover rate	0.7	0.7	0.7	0.7
Mutation rate	0.08	0.08	0.08	0.08

55 mm × 55 mm with nine LEDs, respectively. Four angles of 0°, 90°, 180°, 270° and eight angles of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° are considered for optimization via GA, respectively, for two aforementioned two different sizes if the LCD backlight modules.

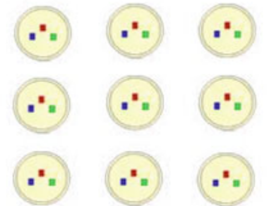
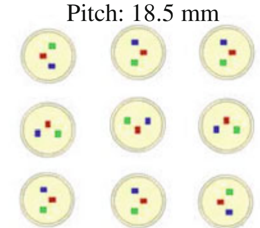
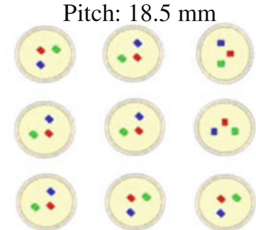
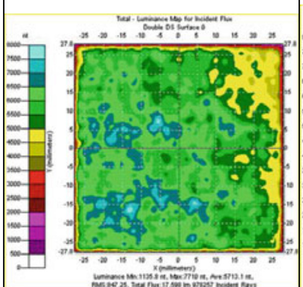
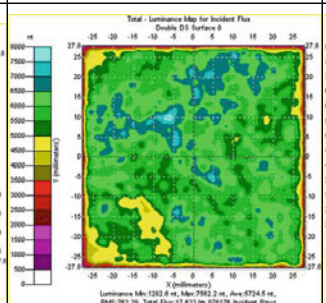
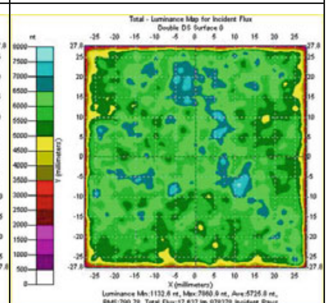
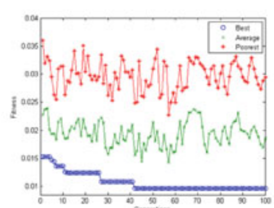
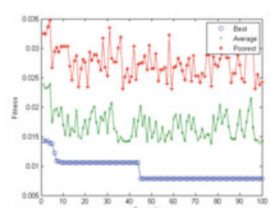
The current study proposes an balanced optimization technique to search for the optimal angular placement

Table 2 Comparison between original and optimized angular placement for the LED BLU with the proposed novel cone-shaped lens by four LEDs

	BLU with Lens	Angular Placement optimized via GA for BLU with Lens	
	Original Angular Placement	Considering 360° divided into 4 angles: 0°, 90°, 180°, 270°,	Considering 360° divided into 8 angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
Optical Film	Diffuser sheet ×2		
Angular Placement of 4 LEDs for BLU	Pitch: 18.5 mm 	Pitch: 18.5 mm 	Pitch: 18.5 mm 
Simulation Results			
Fitness Function of GA	none		
Averaged luminance	5585 nit	5587.5 nit	5579.3 nit
Brightness Uniformity	78.61 %	81.75%	84.59 %
Color difference Δu'v'	0.0339	0.0130	0.0108

pattern of LEDs in the BLU that offers required uniformity and reaches much better color mixing. There are many popular numerical optimization algorithms available nowadays, such as the methods of decent gradient and sequential algorithm. However, for the present problem, we have a large number of design variables in the LED angles. Furthermore, the optimization needs to be performed with the assistance from the TracePro model, which could only be conducted in an off-line fashion with heavy computation load. To solve this complexity, the numerical optimization algorithm, GA, is employed herein to find the optimal angular placement pattern of LEDs, since (1) the optimum

Table 3 Comparison between original and optimized angular placement for the LED BLU with the proposed novel cone-shaped lens by nine LEDs

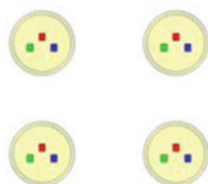
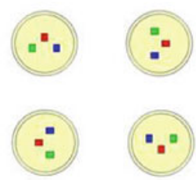
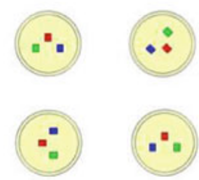
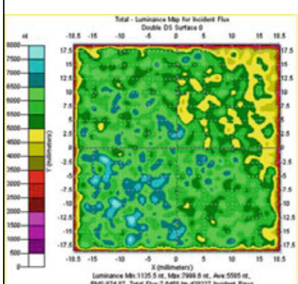
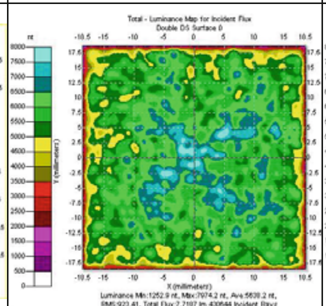
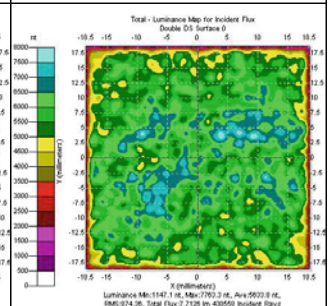
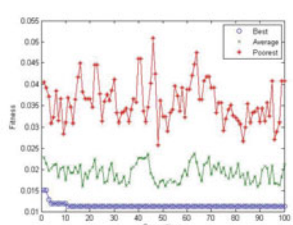
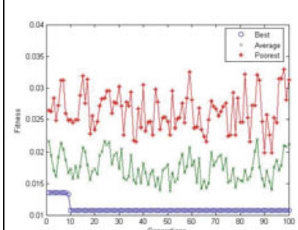
	BLU with Lens	Angular Placement optimized via GA for BLU with Lens	
	Original Angular Placement	Considering 360° divided into 4 angles: 0°, 90°, 180°, 270°,	Considering 360° divided into 8 angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
Optical Film	Diffuser sheet ×2		
Angular Placement of 4 LEDs for BLU	Pitch: 18.5 mm 	Pitch: 18.5 mm 	Pitch: 18.5 mm 
Simulation Results			
Fitness Function of GA	none		
Averaged luminance	5713.1 nit	5724.5 nit	5725.8 nit
Brightness Uniformity	78.47 %	84.34%	88.21 %
Color difference Δu'v'	0.0305	0.00975	0.00780

value is searched without calculating gradients; (2) the advantage of avoiding local optima to reach the global maximum is provided. It could be noted in a number of engineering studies that the GA is already largely used in non-microbiology studies. In the first step of executing GA, a fitness function F to minimize is defined as the maximum of the color difference between any two measuring points on the BLU output plane, denoted by $\Delta u'v'$. According to the CIE (1976) uniform chromaticity scale diagram (Malacara 2002; Ries et al. 2003), $\Delta u'v'$ can be computed by,

$$F = Min(\Delta u'v') = Min\sqrt{\left(u'_1 - u'_2\right)^2 + \left(v'_1 - v'_2\right)^2} \qquad (1)$$

where (u', v') is the coordinates of CIE1976 uniform chromaticity, and $i, j = 1, 2, 3, \ldots, 25$, serve as the indices for 25 measuring points. The locations of 25 measuring

Table 4 Comparison between original and optimized angular placement and changed pitch for the LED BLU with the proposed novel cone-shaped lens by four LEDs

	BLU with Lens	Angular Placement optimized via GA for BLU with Lens	
	Original Angular Placement	Considering 360° divided into 4 angles: 0°, 90°, 180°, 270°,	Considering 360° divided into 8 angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
Optical Film	Diffuser sheet ×2		
Angular Placement of 4 LEDs for BLU	Pitch: 18.5 mm 	Optimized Pitch: 14.5 mm 	Optimized Pitch: 14.5 mm 
Simulation Results			
Fitness Function of GA	none		
Averaged luminance	5585 nit	5638.2 nit	5633.8 nit
Brightness Uniformity	78.61 %	83.85%	85.3 %
Color difference Δu'v'	0.0339	0.0114	0.0106

points are defined by a commercial inspection standard, which are evenly distributed on the output surface of the BLU. The subsequent computation procedure includes determination of the parameters which are length of bit, number of generation, number of population, crossover rate and mutation rate. The complete computation process for optimization is illustrated by a block flow in Fig. 5. Table 1 shows the parameter settings for GA. With settings in hands, it proceeds to initialize a population of variables randomly, and then the initial one is improved through repetitive application of mutation, crossover, and selection operators.

Some of simulation results of the 37 mm × 37 mm and the 55 mm × 55 mm backlight module are shown in

Fig. 6 Photograph of measurement system

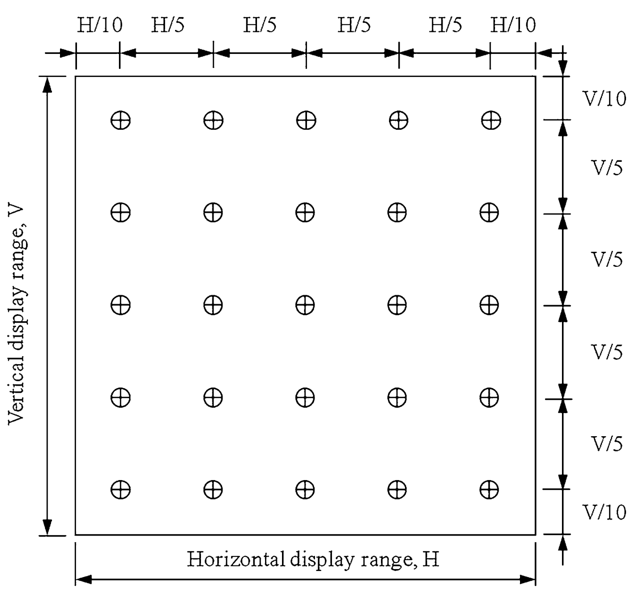


Fig. 7 VESA 25-points measurement

Tables 2 and 3, respectively. In this case of optimization based on Tracepro simulations, LED angles are varied to maximize uniformity and color balance simultaneously. In the 37 mm × 37 mm with four angles considered, having been GA-optimized, the color difference is reduced from 0.0339 to 0.0130 and the average brightness is increased from 78.61 to 81.75 %. Furthermore, with eight angles considered, the improvement is significant both in reducing the color difference from 0.0339 to 0.0108 and increasing the average brightness from 78.61 to 84.59 %. It appears that with eight LED angles available to vary it offers a better design solution in terms of simultaneous low color difference and high uniformity. On the other hand, in the 55 mm × 55 mm module with four angles considered, the color difference is reduced from 0.0305 to 0.00975 while the average brightness is increased from 78.47 to 84.34 %. Besides, with eight angles considered, the improvement is significant both in reducing the color difference from 0.0305 to 0.00780 and increasing the average brightness from 78.47 to 88.21 %. It can also be noted that the optimized LED angles with eight angles available to vary offers a better design solution in terms of simultaneous low color difference and high emission uniformity.

As for the case with the LED spacing (pitch) available to be designated as one of design parameters, the simulation results for the 37 mm × 37 mm module with four and eight LED angles considered as design variables are shown in Table 4. When the LED pitch is changed from 18.5 to 14.5 mm, having been GA-optimized, the optimal pitch is found to be 14.5 mm. Furthermore, the color difference is reduced from 0.0339 to 0.0114 while the average brightness is increased from 78.61 to 83.85 %. With eight angles considered, the improvement is significant both in reducing the color difference from 0.0339 to 0.0106 and increasing the average brightness from 78.61 to 85.30 %. It appears that with LED pitch optimized, even better color balance and uniformity are achieved as compared to that without LED pitch to be optimized. Finally, it should be noted at this point that more than eight placement angles for a single LED can be considered for GA optimization such that better color balance is supposed to be obtained; however, it was found eventually converges to the best color balance, i.e., the smallest color difference close to zero in an exponential fashion, not in a linear relationship. In light of saving computation, the consideration of eight varied LED angles is found sufficient to reduce color difference to a required small level.

4 Numerical and experimental results

The comparison between numerical and experimental results is conducted to confirm the accuracy of the established simulation models. The experimental system as shown in Fig. 6 is set up in laboratory to measure brightness, uniformity, and color content by the instrument Topcon BM-7. A sample LED backlight module is built following closely the standard measurement procedure of CIE 127, as depicted in Fig. 7. Table 5 shows the comparison between simulation and measurement results for the 37 mm × 37 mm backlight module. Based on the measurement results, in the case of four angles and changed pitch, the color difference is reduced from 0.0288 to 0.0221 while the average brightness is increased from 84.96 to 89.14 %. Besides, with the case of eight angles and changed pitch considered, further improvement is significant both in reducing the color difference from 0.0288 to 0.0192 and increasing the

Table 5 Experimental measurements of comparison between original and optimized angular placement and changed pitch by four LEDs

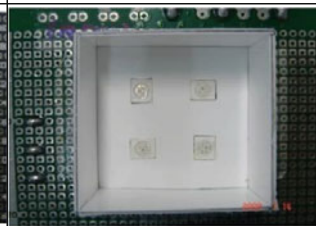
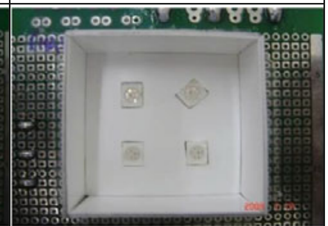
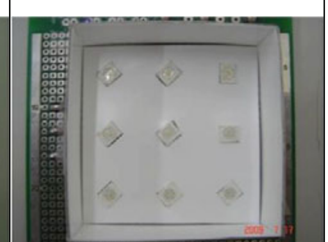
	Original Angular Placement		Considering 360° divided into 4 angles: 0°, 90°, 180°, 270°,		Considering 360° divided into 8 angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°	
Angular Placement of 4 LEDs						
LED Pitch	18.5 mm		14.5 mm		14.5 mm	
	Simulation	Measurement	Simulation	Measurement	Simulation	Measurement
Averaged luminance	5585 nit	5250.6 nit	5638.2 nit	5481.4 nit	5633.8 nit	5403.2
Brightness Uniformity	78.61%	84.96%	83.85%	89.14%	85.30%	91.25%
Color difference Δu'v'	0.0339	0.0288	0.0114	0.0221	0.0106	0.0192

Table 6 Experimental measurements of comparison between original and optimized angular placement by nine LEDs

	Original Angular Placement		Considering 360° divided into 4 angles: 0°, 90°, 180°, 270°,		Considering 360° divided into 8 angles: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°	
Angular Placement of 9 LEDs						
LED Pitch	18.5 mm		18.5 mm		18.5 mm	
	Simulation	Measurement	Simulation	Measurement	Simulation	Measurement
Averaged luminance	5713.1 nit	5472.7 nit	5724.5 nit	5598.8 nit	5725.8 nit	5613.4
Brightness Uniformity	78.47%	86.97%	84.34%	88.96%	88.21%	91.9%
Color difference Δu'v'	0.0305	0.0267	0.00975	0.0176	0.0078	0.0165

average brightness from 84.96 to 91.25 %. In the next step, a larger 55 mm × 55 mm backlight module as shown in Table 6 is manufactured and tested for experimental validation. A general closeness is present between the counterparts, furthermore, the trends of optimization are the same—the uniformity is increased while color balance is reduced. Another observation is that the simulated brightness uniformities are generally lower than experimental, while the color balance by the optimized LED angles via simulation is slightly better than experimental counterparts.

5 Conclusion

A directly-lit backlight module with LED capped with novel cone-shaped lens is optimized via GA in this study to achieve simultaneous high color balance and emission uniformity. The color difference and the average brightness of the 37 mm × 37 mm and 55 mm × 55 mm LEDs backlight modules are improved by optimizing by GA via changing LED placement angles and spacing pitch. While performing GA-optimization, the consideration of eight varied LED angles is found sufficient to reduce color difference to a required small level. Experimental results show that the color difference could be reduced and the average brightness could be increased via the optimized placement angles of LEDs. In the 33 mm × 33 mm LEDs backlight module with eight angles and pitch varying, the average brightness is enhanced to 91.25 % and the color difference is decreased to 0.0192. The average brightness is increased to 91.9 % and the color difference is reduced to 0.0165 in the 55 mm × 55 mm LEDs backlight module with eight LED placement angles considered. The aforementioned achieved color balance and uniformity present the successful designs proposed by the current study.

Acknowledgments The author appreciate the support from National Science Council of R.O.C under the grant no. NSC 101-2623-E-009-006-D and 100-2221-E-009-091. This work was also supported in part by the UST-UCSD International Center of Excellence in Advanced Bio-Engineering sponsored by the Taiwan National Science Council I-RiCE Program under Grant NSC-100-2911-I-009-101.

References

Chang R-S, Tsai J-Z, Li T-Y, Liao H-L (2012) LED backlight module by light guide-diffusive component. IEEE J Disp Technol 8(2):79–89

Chao PC-P, Liao L-D, Chiu C-W (2006) Design of a novel LED lens cap and optimization of LED placement in a large area direct backlight for LCD-TVs. In: Proceedings of SPIE, 6196, pp 61960N

Chao PC-P, Liao L-D, Chiu C-W (2007) A light-guiding cap for LEDs, a patent application filed to TIPO: I286613, Intellectual Property Office of Taiwan, R.O.C., and USPTO, United State Patent and Trademark Office

Chao PC-P, Shen C-Y, Chiu C-W, Huang J-S, Kao Y-Y, Tu T-Y, Wang C-L, Lin H-W, Chi S, Tsai S-Y (2008) A novel lens cap designed for the RGB LEDs installed in an ultra-thin and directly lit backlight unit of large-sized LCD TVs. J SID 16(2):317–332

Chiu CW, Shen CY, Chao CP (2007) Novel lens design and experimental verification for high efficiency direct type backlight module of LCD-TV, Asian Pacific Conference on Optics Manufacture

Folkerts W (2004) LED backlighting concepts with high flux LEDs, SID 04 Digest, pp 1226–1229

Hao DJ, Qian KY, Luo Y (2011) Use of adjusted molecular dynamics method for dot pattern design in large scale light-emitting diode edge-lit backlight unit. Opt Eng 50(104001):1–6

Huang W, Li J-M, Yang L-M, Jin Z-L, Zhong Z-G, Liu Y, Chou Q-Y, Li F (2011) Local dimming algorithm and color gamut calibration for RGB LED backlight LCD display. Opt Laser Technol 43:214–217

Käläntär K, Okada M (2004) RGB-LED backlighting Monitor/TV for reproduction of images in standard and extended color spaces. IDW 04:683–686

Lin C-F, Wu C-C, Yang P-H, Kuo T-Y (2019) Application of Taguchi method in light-emitting diode backlight design for wide color gamut displays. IEEE J Disp Technol 5(8):323–330

Malacara D (2002) Color vision and colorimetry: theory and applications, SPIE Press

Martynov Y, Konijn H, Pfeffer N, Kuppens S, Timmers W (2003) High-efficiency slim LED backlight system with mixing light guide, SID 03 Digest, pp 1259–1261

Moreno I, Contreras U, Tzonchev RI (2005) Cluster configurations of red, green, and blue LEDs for white light. In: Proceedings of SPIE 5739:162–168

Ries H, Leike I, Muschaweck J (2003) Mixing colored LED sources, Proceedings of SPIE, 5186:27–32

Schubert EF (2006) Light-Emitting Diodes, Cambridge University Press, New York, pp 277–280

West RS, Konign H, Kaypens S et al (2003) High brightness direct LED backlight for LCD-TV, SID 03 Digest, pp 1262–1265