

Application of Taguchi Method in Light-Emitting Diode Backlight Design for Wide Color Gamut Displays

Chi-Feng Lin, Chih-Cheng Wu, Po-Hua Yang, and Tsung-Yuan Kuo

Abstract—This paper utilizes the Taguchi design method to optimize the design parameters of a light-emitting diode (LED) backlight unit for wide color gamut liquid crystal displays (LCDs). In optimizing the design, the parametric analyses consider two particular regions of the backlight unit, namely, the color-mixing zone and the extractor zone. The Taguchi experiments are configured in $L_9(3^4)$ orthogonal arrays and are designed to evaluate the effects of the design parameters on the color-difference, optical efficiency and luminance of the unit. The analysis of variance (ANOVA) results reveal that the optical efficiency and color-difference properties are determined primarily by the reflector design and the length of the color mixing zone, respectively, while the luminance to the LCD panel is affected principally by the taper angle of the optical microstructures in the extractor zone. The optimal design parameters of the color-mixing zone and extractor zone are estimated from the Taguchi S/N ratio data and the ANOVA results, and are verified via ray-tracing simulations. For an input flux of 1501 lm, the optimal design shows 0.01 of the color differences in CIE 1976 color space, 85% of the optical efficiency, and 10675 nits of luminance. Thus, the optimized backlight unit provides an ideal solution for the illumination of large-scale LCD display devices.

Index Terms—Color mixing, light-emitting diode (LED) backlight, optical microstructure, Taguchi method.

I. INTRODUCTION

RECENT years have witnessed a strong shift in consumer demand toward slim, large-scale display units for such applications as TV viewing, gaming, computing, and so forth. In response to this requirement, manufacturers have invested huge amounts of R&D resources in developing high-performance liquid crystal displays (LCDs) [1]–[3]. Since liquid crystals are a non-light-emitting material, such devices utilize a backlight unit positioned beneath the LCD panel to illuminate the image. The characteristics of the backlight unit, e.g., the luminance uniformity and the brightness, have a fundamental effect upon the image quality, and thus manufacturers have

explored the relative merits of many different backlight configurations. In general, however, modern backlight units can be classified as either “bottom lit” or “side lit”, depending on the position of the light sources relative to the display screen. In bottom-lit units, the light sources are configured directly beneath the LCD panel, and thus a sufficient distance must be preserved between the emitting surface and the light sources to ensure a uniform lighting effect. Consequently, bottom-lit backlight units are more commonly used in large-scale display devices with thicknesses of around 20 ~ 50 mm. As implied by their name, the light sources in edge-lit backlight units are positioned to one side of the LCD panel, and the light is transmitted through a light guide containing a pattern of light-scattering dots carefully designed such that the light is distributed uniformly over the undersurface of the LCD panel. In the design process, the thickness of backlight units could be a major concern. In general, the edge-lit backlight units are implemented with light guide plates. They tend to have a much smaller thickness than the bottom-lit backlight units.

Light-emitting diodes (LEDs) have many favorable characteristics, including a small form factor, a low power consumption, an instant power-on capacity, and an absence of mercury or any other form of toxic substance. As a result, they have attracted considerable attention from LCD manufacturers as a potential light source for backlight units. However, compared with traditional line light sources, such as cold cathode fluorescent lamps (CCFLs), achieving a uniform illumination distribution using multiple LED point light sources is far more challenging. Previous researchers have attempted to resolve this problem by using mixing light guides or light guide buffer plates to increase the light scattering angle [4]–[6], or by adding a secondary optical element to the backlight unit to distribute the light emitting angles of the light guide in such a way as to achieve the desired illumination pattern [7], [8]. However, in addition to improving the homogeneity of the light emitted by the light guide, increasing the luminance (i.e., the brightness) in the direction normal to the surface of the LCD panel is also an important concern. Traditionally, this has been achieved by positioning one or two Brightness Enhancement Films (BEFs) above the diffuser layer between the light guide and the LCD panel. However, the use of BEFs has a number of practical disadvantages, including a more complex manufacturing process and an increased cost. Thus, in recent years, researchers have attempted to avoid the requirement for BEF films by replacing the light-scattering dots printed on the light guide plate by optical microstructures known as extractors in order to more accurately control the direction of

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the light reflected/scattered by the light guide structure [9]–[11]. Although these extractors yield a significant improvement in the brightness properties of the backlight unit, they complicate the task of achieving a uniform illumination of the LCD panel. Nonetheless, previous studies have shown that this problem can be resolved through the use of optical simulations based upon appropriate models and optimization criteria [12]–[14].

Traditional LCD display devices with CCFL-type illumination sources have a narrower color gamut than cathode ray tube (CRT) monitors. However, with the development of high-brightness LEDs in the 1990's, it has been shown that a color gamut wider than the standard set by the National Television System Committee (NTSC) can be achieved through an appropriate combination of red, green, and blue (RGB) LEDs [15]. Clearly, the use of RGB LEDs as an illuminating source in LCD display units requires some form of color-mixing mechanism to achieve a uniform color distribution. It was shown in [7] that this could be accomplished by adding an additional optical element to the LED panel. However, researchers and manufacturers generally prefer to incorporate a specially designed color-mixing zone within the backlight unit to achieve a uniform distribution of the individual colors [4].

In general, satisfying the requirement for low-cost, energy-efficient, wide color gamut, slim-type LCD displays calls for the use of LED light sources on environmental and color range grounds, edge-lit backlight units on space-saving grounds, and modularized functional units on ease-of-assembly grounds. In practice, however, optimizing the performance of such display devices inevitably requires certain trade-offs to be made between competing aspects of the design. For example, the light source module presented in [16] enhanced the color saturation and light uniformity of the backlight unit, but reduced its optical efficiency. Furthermore, the magnitude and angular distribution of the emitted luminance of an edge-lit backlight unit are fundamentally dependent not only upon the size and shape of the extractors, but also upon the detailed design of the color-mixing region (e.g., the arrangement of the LEDs, the geometry and optical properties of the reflector, and so forth).

Clearly, the use of trial-and-error methods to solve such multi-objective optimization problems is impractical on both time and expense grounds. In recent years, researchers have demonstrated the power of the Taguchi experimental design method in solving complex optimization problems in a diverse range of fields [17]–[19]. Accordingly, this study applies the Taguchi method to solve the problem of optimizing the design of an edge-lit backlight unit for energy-efficient, wide color gamut, high-luminance, slim-type LCD display devices. The aim of the Taguchi experiments is to identify the design settings which enhance the color-difference, optical efficiency and luminance properties of the backlight unit. The experiments address two specific regions of the backlight unit, namely the color-mixing zone and the extractor zone, respectively, and consider such design parameters as the reflector design, the LED arrangement and the LED radiation pattern in the color-mixing zone, and the extractor shape, extractor taper angle and light guide angle in the extractor zone, respectively. The validity of the optimal design is confirmed by performing a series of ray-tracing simulations.

II. SIMULATION SETUP

The Taguchi method is a powerful experimental design tool developed by Taguchi and Konishi [17]–[20] for solving the engineering problems of optimizing the performance, quality and cost of a product or process in a simpler, more efficient and systematic manner than traditional trial-and-error processes. In the proposed approach, the parameters which are assumed to exert the greatest influence on quality of the design process are configured in an orthogonal array designed in such a way as to randomize the conducted experiments. The quality of the design solution obtained from each run in the orthogonal array is evaluated using a signal-to-noise (S/N) ratio. Depending on the experimental objective, different quality characteristics may be pertinent. For example, in the optimization problem considered in the present study, the characteristics of interest include the color difference, the optical efficiency (i.e., the output flux/the input flux) and the luminance. Having conducted all the experimental trials prescribed in the orthogonal array, the analysis of variance (ANOVA) statistical method is applied to identify the design parameters which have a statistically significant effect upon the design result. The optimal combination of design parameters is then predicted based on the ANOVA results. Note that full details of the S/N ratio and the ANOVA analyses are presented in Section III.

The Taguchi method commences by defining an appropriate set of performance measures and corresponding target values for the optimization process. In the optimization problem considered in this study, the performance measures include the color difference, the optical efficiency and the luminance of the backlight unit, respectively. Note that the target values need not necessarily be a maximum value. For example, in the current case, the aim is to minimize the color difference within the color-mixing zone. Having selected the performance criteria for the optimization process, a decision is then made as to the design parameters which are likely to exert the greatest effect on these criteria. For example, the ability of the backlight unit to minimize the color difference is directly affected by the design of the reflector and LED configuration within the color-mixing zone. Each selected design parameter, designated in the Taguchi methodology as a “control factor”, is then assigned a prescribed number of possible design settings (“level settings”). For example, the present Taguchi trials consider three different reflector designs and LED configurations. Note that the level settings for each control factor are spread within a range defined by current manufacturing capabilities or based upon an inspection of the available industrial design data. In accordance with the number of control factors and level settings defined in the previous steps, a suitable Taguchi orthogonal array is chosen to configure the experimental trials. For example, the performance of the color-mixing region of the backlight unit is governed by four control factors, each with three level settings. Accordingly, the Taguchi trials are configured in an $L_9(3^4)$ orthogonal array, which prescribes a total of nine experimental runs. Having completed the experimental trials, S/N ratios are computed for each experimental run and the ANOVA statistical analysis method is then applied to determine the respective effects of the different design parameters on the specified performance

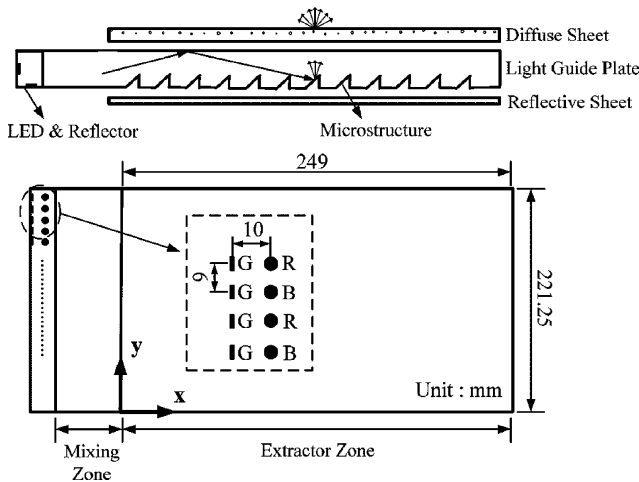


Fig. 1. Schematic illustration of edge-lit backlight unit.

measures. Based upon the statistical results, the optimal levels of each control factor are identified and are used in a final experiment to confirm the optimality of the design.

The original intention of this study was to optimize the design of an edge-lit backlight unit for large size (i.e., 40”) flat-screen LCD TVs. However, manufacturing backlight units of such a size presents a considerable challenge, particularly in the injection molding process. Thus, in performing this study, the backlight unit was divided into eight identical units and the Taguchi experiments considered just one of these units when optimizing the backlight design. Fig. 1 presents a schematic illustration of the optical model considered in the present study. (Note that the width of the light emitting surface is around one fourth the length of a 40” LCD screen, while its length is approximately one half the width of a 40” LCD screen.) The basic parameters considered when constructing the optical model are summarized in Table I. As shown, the diffuser scattering pattern is based on the measured BSDF curve of a commercial diffuser (ET_166A, Exploit Technology Company, Ltd.). In addition, it is noted that the backlight unit comprises a total of 48 RGB LEDs. As shown in Fig. 1, the backlight unit comprises a color-mixing zone containing a reflector and two rows of LEDs and an extractor zone containing an arrangement of optical microstructures and a light guide plate. The light emitted by the LEDs is directed into the color-mixing zone by the reflector and then enters the extractor zone, where it is reorientated and redistributed in such a way as to achieve a uniform illumination of the overlying LCD panel. In enhancing the optical performance of the backlight unit, the analyses commence by optimizing the design parameters of the color-mixing zone in such a way as to achieve an optical efficiency of at least 80% and a color-difference of 0.01 [4], [7]. Having done so, the analyses optimize the design of the optical microstructures and light guide plate in order to produce an emitted luminance greater than 10 000 nit [7] in the direction normal to the LCD panel.

In practice, the color-difference and optical efficiency properties of the color-mixing zone are determined by four factors, namely: (A) the reflector design and the relative positions of the LEDs; (B) the LED radiation pattern; (C) the optical properties of the reflector; and (D) the length of the color-mixing zone. As

TABLE I
BACKLIGHT SYSTEM PARAMETERS

Type	value
The size of LED	2 mm × 2 mm × 0.7 mm
Reflective index of reflector	95%
Material of light guide	PMMA (n=1.49)
Transmittance of diffuser	91%
Diffuser scattering pattern	Measured BSDF curve
CIE xy coordinate of red LED	(0.698, 0.302)
CIE xy coordinate of green LED	(0.181, 0.759)
CIE xy coordinate of blue LED	(0.126, 0.065)
CIE xy coordinate of white point	(0.351, 0.335)
Ratio luminous of LED (R:G:B)	4.548 : 8.356 : 1
Ratio of number (R:G:B)	1 : 2 : 1
Total number of LED	48
Total luminous	1501 lm
Simulation mesh dimensions	21×21
Simulation rays	20,000,000

TABLE II
CONTROL FACTORS AND LEVEL SETTINGS FOR COLOR-MIXING ZONE

Symbol	Parameter description	Level 1	Level 2	Level 3
A	Reflector design and LED arrangement	Design 1	Design 2	Design 3
B	LED radiation pattern	Side emitting	Lambertian	Side emitting + Lambertian
C	Optical property of reflector	Mirror	Lambertian	50% Mirror + 50% Lambertian
D	Length of color mixing zone	10 mm	20 mm	30 mm

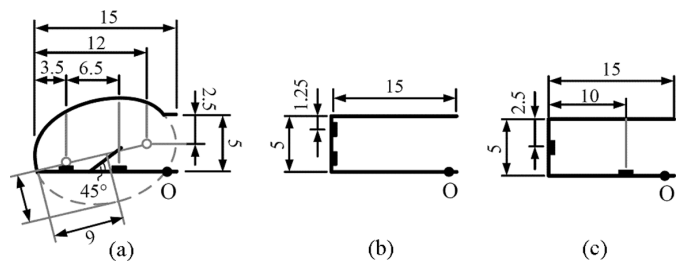


Fig. 2. Reflector design and LED positions in: (a) Design 1, (b) Design 2, and (c) Design 3.

shown in Table II, in the Taguchi experiments, each of these four control factors is assigned three possible level settings. Fig. 2 illustrates the three reflector design/LED arrangements. In Design 1, the reflector has an elliptical profile and the two rows of LEDs are both located on the lower surface of the reflector. As shown, the LEDs farthest from Point 0 (i.e., the virtual intersection point of the elliptical reflector profile with the horizontal surface of the backlight unit) are placed at the first focal point of the elliptical reflector such that the reflected light passes through the second focal point before entering the extractor zone. Meanwhile, the second row of LEDs (i.e., the LEDs closer to Point 0) are positioned beneath a flat reflector tilted at an angle of 45°

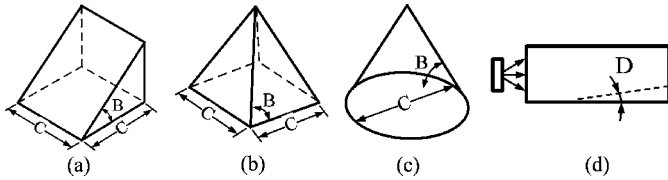


Fig. 3. Schematic illustration of shape and geometry parameters of different optical microstructures. (a) Prism. (b) Pyramid. (c) Cone. (d) Wedge angle of light guide.

to the horizontal in order to increase the intensity of the light emitted into the extractor zone. As shown in Fig. 2(b) and (c), Designs 2 and 3 both consider a reflector with a rectangular profile. The difference in the two designs lies in the configuration of the LEDs. Specifically, in Design 2, both rows of LEDs are positioned on the vertical surface of the reflector, while in Design 3, one row of LEDs is positioned on the lower surface of the reflector, while the other is positioned on the vertical surface. In conducting the Taguchi experiments, the LEDs are assumed to have either a side-emitting radiation pattern, a Lambertian radiation pattern, or a side emitting+Lambertian radiation pattern. In modeling the side-emitting pattern, the experiments consider the color-mixing zone to be fitted with Luxeon Emitter LEDs (LXHL-DM01). In the case of the side-emitting+Lambertian pattern, the LEDs in the row closer to Point O are set to side-emitting, while those in the second row are set to Lambertian. In conducting the Taguchi trials, the reflector is assumed to have either a perfect mirror-like surface, a Lambertian surface, or a mirror-like+Lambertian surface. Finally, the color-mixing zone is assumed to have a length of either 10, 20, or 30 mm.

The optical performance of the extractor zone in the backlight unit can be quantified by the luminance of the light emitted through the upper surface in the direction normal to the LCD panel. In general, the luminance of the emitted light depends on four factors, namely (A) the shape of the extractors; (B) the taper angle of the extractors; (C) the size of the extractors; and (D) the wedge angle of the light guide. In the present Taguchi analyses, these control factors are each assigned three possible level settings (see Table III). As shown in Fig. 3, the extractors are considered to have either a pyramid, prism or conical form. Clearly, the taper angle of the individual extractors [angle B in Fig. 3(a)–(c)] should be optimized in such a way as to match the angle of the light emitted from the color-mixing region of the backlight unit. Thus, as shown in Table III, the taper angle control factor is assigned three different values, namely 30°, 35°, or 40°. Finally, the extractor size (i.e., the side length or diameter dimension) is specified as either 0.2 mm, 0.4 mm or 0.6 mm, while the wedge angle of the light guide plate is assigned a value of 0°, 0.2°, or 0.4°.

Having specified the control factors and level settings for the color-mixing zone and extractor zone, respectively, Taguchi experiments were performed to investigate the relative effect of each control factor/level setting on the color-difference, optical efficiency and luminance properties of the backlight unit (as evaluated using ray-tracing simulations). Having completed the Taguchi trials, the experimental results were analyzed using statistical techniques in order to identify the optical design parameters.

TABLE III
CONTROL FACTORS AND LEVEL SETTINGS FOR EXTRACTOR ZONE

symbol	Parameter description	Level 1	Level 2	Level 3
A	Extractor shape	Pyramid	Prism	Cone
B	Extractor taper angle	30°	35°	40°
C	Extractor Dimension	0.2 mm	0.4 mm	0.8 mm
D	Wedge angle of light guide	0°	0.2°	0.4°

TABLE IV
 $L_9(3^4)$ ORTHOGONAL ARRAY FOR COLOR-MIXING ZONE TAGUCHI TRIALS

Exp. No.	A	B	C	D	Color difference $\Delta u'v'$	Efficiency (%)	η of efficiency	η of color difference
1	1	1	1	1	0.052	71.85	37.129	25.744
2	1	2	2	2	0.039	61.22	35.738	28.217
3	1	3	3	3	0.019	50.71	34.101	34.023
4	2	1	2	3	0.017	90.61	39.143	35.65
5	2	2	3	1	0.041	94.05	39.467	27.723
6	2	3	1	2	0.046	85.21	38.609	26.764
7	3	1	3	2	0.024	61.67	35.802	32.579
8	3	2	1	3	0.019	76.99	37.728	34.425
9	3	3	2	1	0.028	81.46	38.218	31.088

III. ANALYSIS OF TAGUCHI EXPERIMENTAL DATA

A. Color-Mixing Zone

As discussed in the previous section, the performance of the color-mixing region of the backlight unit is governed by four control factors, each with three level settings. Accordingly, the Taguchi trials were configured in an $L_9(3^4)$ orthogonal array, as shown in Table IV. Note that for each factorial combination, the table also presents the corresponding results for the color difference and optical efficiency, respectively. In the Taguchi methodology, the quality of any particular design solution is quantified using a S/N ratio. The form of this ratio depends on the particular aspect of the product or process being optimized, and can be generalized as either “nominal is best,” “smaller is better,” or “larger is better” [21]. In the current Taguchi experiments, the objective is to reduce the color difference of the light exiting the color-mixing region to a value of less than 0.01 whilst simultaneously ensuring an optical efficiency of at least 80%. Consequently, the success of any factorial combination in reducing the color difference is evaluated using the smaller-the-better S/N ratio, while the effect of the parameter settings in improving the optical efficiency is quantified using the larger-the-better S/N ratio, i.e.,

$$\text{Smaller the better: } \eta = -10 \log \frac{\sum_{i=1}^n y_i^2}{n} \quad (1)$$

$$\text{Larger the better: } \eta = -10 \log \frac{\sum_{i=1}^n \frac{1}{y_i^2}}{n} \quad (2)$$

where y_i denotes the value of the color difference or the optical efficiency associated with the i th test, i is the index number of

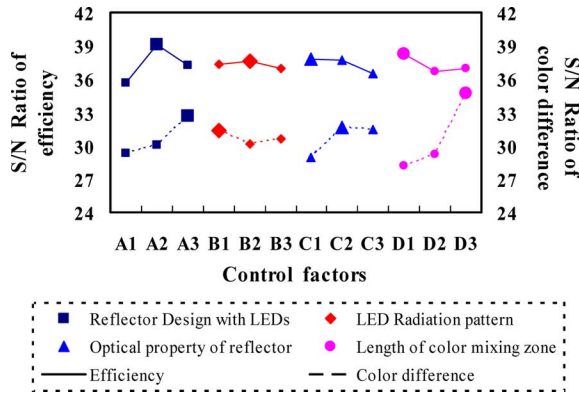


Fig. 4. S/N ratios of color-difference and optical efficiency properties at different levels of color-mixing zone control factors.

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

The effect of a particular design parameter on the color difference and optical efficiency of the color-mixing region can be evaluated by computing the average value of the corresponding S/N ratio over each of the three level settings for that particular parameter. The corresponding results are presented in tabular form in the two right-most columns of Table IV and are illustrated graphically in Fig. 4. The optimal design parameters are easily found by identifying the particular factorial combinations in Fig. 4 which yield the highest values of the two S/N ratios. Thus, from inspection, the parameter settings which optimize the optical efficiency of the color-mixing zone are found to be as follows: A2 (Reflector design: Design 2), B2 (LED radiation pattern: Lambertian), C1 (Reflector property: Mirror) and D1 (Color-mixing zone length: 10 mm). Each of these results is intuitively reasonable. For example, a simple reflector design and LED configuration (i.e., Design 2) can be expected to yield a better optical efficiency than a complex design, such as Design 1 (see Fig. 2). Furthermore, a Lambertian radiation pattern provides a greater number of possible paths for the light emitted from the LEDs to exit the color-mixing region than a side-emitting pattern, and, therefore, improves the optical efficiency. Meanwhile, a mirror-like reflector minimizes light losses within the color-mixing region, and therefore increases the amount of light supplied to the extractor zone. Finally, a shorter color-mixing region minimizes the amount of light energy absorbed during the mixing process, and hence increases the amount of light energy transferred to the extractor region of the backlight unit. In a verification experiment performed using the parameter settings A2-B2-C1-D1, the optical efficiency was found to be 95.54%, i.e., higher than that obtained using any of the original factorial combinations (see Table IV). Thus, from an optical efficiency perspective, parameter settings A2-B2-C1-D1 represent the optimal design parameters for the color-mixing zone of the backlight unit. However, the corresponding value of the color difference was found to be 0.1026, i.e., higher than the target value of 0.01.

From an inspection of Fig. 4, the optimal design parameters from a color difference perspective are determined to be as follows: A3 (Reflector design: Design 3); B1 (LED radiation pattern: Side-emitting); C2 (Reflector property: Lambertian); and

D3 (Color-mixing zone length: 30 mm). Again, these results are not unexpected. For example, in Design 3, the two rows of LEDs are configured in a mutually orthogonal arrangement, and thus a greater color mixing effect is achieved. Similarly, the combined effect of a side-emitting radiation pattern from the LEDs and a Lambertian surface property of the reflector improves the light scattering properties of the illuminating light and therefore produces a more uniform color mixing effect. Moreover, the uniformity of the white light produced in the mixing process improves with a greater mixing distance as a consequence of the dispersion of the individual colors. The results of a ray tracing analysis showed that these parameter settings yielded a color difference of just 0.0114, i.e., lower than that achieved in any of the original Taguchi experimental trials. However, the corresponding value of the optical efficiency was found to be just 78.58%.

Overall, the results presented above indicate that the parameter settings which optimize the optical efficiency result in a notable increase in the color difference, while those which optimize the color difference cause a significant reduction in the optical efficiency. In other words, a trade-off must be made between these two performance criteria when optimizing the design of the color-mixing zone. As described in the following section, this is achieved in the Taguchi methodology by applying the ANOVA statistical technique to the S/N ratio data acquired from the experimental trials.

B. Application of Anova Technique to Analysis of Color-Mixing Zone Parameters

In estimating the cause-and-effect relationship between the design factors and the performance quality utilizing the ANOVA technique, it is assumed that factors with a higher level of statistical significance have a greater effect on the quality metric than those with a lower level of significance. The strength of the effect can be quantified via the percentage contribution parameter ρ , defined as

$$\rho = \frac{SS_d}{SS_T} \quad (3)$$

$$SS_T = SS_d + SS_e \quad (4)$$

where SS_d is the sum of the squared deviations and SS_e is the sum of the squared error. (Note that in the current analysis, SS_e is approximated as 0 since the simulations are repeatable.) The total sum of the squared deviations SS_T from the total mean S/N ratio η_m can be expressed as [22]

$$SS_T = \sum_{i=1}^{n_i} (\eta_i - \eta_m)^2 \quad (5)$$

where n_i is the number of experiments in the orthogonal array and η_i is the mean S/N ratio of the i th experiment.

Table V summarizes the ANOVA results for the color-difference and optical efficiency properties of the color-mixing region of the backlight. The results show that the color-mixing effect is determined primarily by the length of the color-mixing zone (Factor D, 68.25%) and the reflector design/LED configuration (Factor A, 17.47%). Similarly, the optical efficiency is governed chiefly by the reflector design/LED configuration (Factor A, 68.07%) and the length of the color-mixing zone

TABLE V
ANOVA RESULTS FOR COLOR DIFFERENCE AND EFFICIENCY

Target		A	B	C	D
Color difference	SS _d	18.893	2.186	13.266	73.818
	Contribution (%)	17.47	2.02	12.26	68.25
Efficiency	SS _d	17.541	0.674	3.423	2.52
	Contribution (%)	68.07	2.62	13.28	16.03

(Factor D, 16.03%). Note that even though the same factors exert the greatest effect on both the color difference and the optical efficiency, the results presented in the previous section have shown that the parameters settings which yield the greatest optical efficiency (i.e., A2-B2-C1-D1) differ from those which produce the smallest color difference (i.e., A3-B1-C2-D3). Thus, a single optimal design cannot be achieved without compromising one or other of the two design objectives. In general, the overriding objective of the color-mixing zone is to optimize the color uniformity of the output light. Consequently, the optimal design parameters for the color-mixing region should be evolved from the parameter settings which optimize (i.e., minimize) the color difference. Thus, Factors A3 and D3 are carried forward into the optimal design in accordance with Taguchi's half-fraction rule [21]. To ensure that the optimal design also takes account of the need to enhance the optical efficiency of the color-mixing region, at least one of the two remaining entries in the design (i.e., Factors B and C) should be specified in accordance with the ANOVA results obtained for the optical efficiency property. Table V shows that Factor C exerts a greater effect on the optical efficiency than Factor B, and thus parameter C1 is taken into the optimal design. Having specified the parameter settings for Factors A, C and D, the only remaining factor, i.e., Factor B (the radiation pattern), can be specified as required to optimize the overall performance. In attempting to restrict the color difference to a value less than the specified value of 0.01, a change of the parameter values from their preset level settings in the original orthogonal array may be required. From Table V, it is evident that the length of the color-mixing zone has the greatest effect of any of the design parameters on the color-mixing result. Specifically, the color-mixing performance improves as the length of the color-mixing zone is increased (see Fig. 4). Fig. 5 illustrates the variation in the color-difference and optical efficiency properties as a function of the length of the color-mixing zone for four different factorial combinations, i.e., the original combination (A3-B1-C2) and three modified factorial combinations. The figure shows that for all four combinations, the color difference falls below the desired value of 0.01 for all values of the color-mixing length greater than 40 mm. More importantly, the modified factorial combination A3-B3-C1-D* yields the highest optical efficiency of the four combinations (i.e., ~ 85%). Consequently, the true optimal design parameters for the color-mixing zone of the backlight unit are determined to be A3-B3-C1-D(40 mm).

C. Extractor Zone

Having optimized the color-mixing zone, a further series of Taguchi experiments was performed to determine the optimal parameters of the extractor zone given the assumption of an

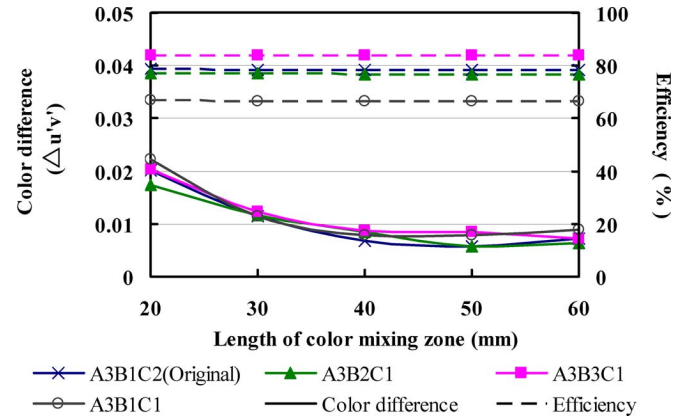


Fig. 5. Variation of color-difference and optical efficiency properties with length of color mixing zone for original factorial combination and three modified factorial combinations, respectively.

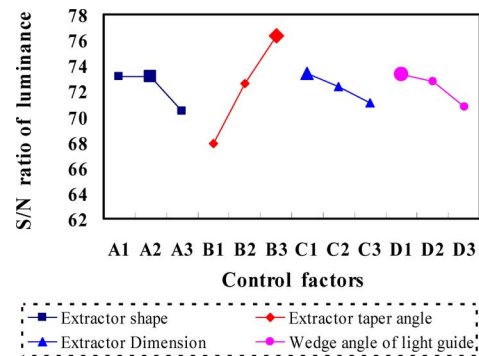


Fig. 6. S/N ratio of normal luminance at different levels of extractor zone control factors.

TABLE VI
 $L_9(3^4)$ ORTHOGONAL ARRAY FOR EXTRACTOR ZONE TAGUCHI TRIALS

Exp	A	B	C	D	Nit	S/N
1	1	1	1	1	3524.60	70.94
2	1	2	2	2	5010.05	73.99
3	1	3	3	3	5261.01	74.42
4	2	1	2	3	2322.71	67.32
5	2	2	3	1	4670.15	73.39
6	2	3	1	2	8727.99	78.82
7	3	1	3	2	1857.42	65.38
8	3	2	1	3	3317.76	70.42
9	3	3	2	1	6047.32	75.63

ideal color-mixing zone. As described in Section II, the performance of the extractor zone (i.e., the luminance in the normal direction) is governed by four factors, each with three level settings (see Table III). Accordingly, the Taguchi experiments were once again configured in an $L_9(3^4)$ orthogonal array. Table VI summarizes the factorial combinations for each simulation run and presents the corresponding values of the luminance and S/N ratio, respectively. Note that for each factorial combination, the simulations were repeated iteratively using a different extractor distribution each time until a luminance uniformity of ~ 85% was obtained. Fig. 6 plots the S/N ratio data in the right-most column of Table VI in a graphical form and shows that the optimal design parameters for the extractor zone are as follows: A2 (Extractor shape: Prism), B3 (Extractor taper angle: 40°),

TABLE VII
ANOVA RESULTS FOR NORMAL LUMINANCE

Target		A	B	C	D
Normal luminance	SS _d	14.289	106.623	8.159	11.16
	Contribution (%)	10.19	76.03	5.82	7.96

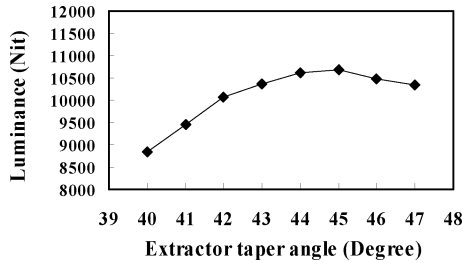


Fig. 7. Variation of normal luminance with prism taper angle.

C1 (Extractor dimension: 0.2 mm), and D1 (Light guide wedge angle: 0°). Thus, the results suggest that the luminance of the light emitted from the extractor unit improves with a prism-like optical microstructure and an increasing taper angle, but reduces with an increasing extractor dimension and light guide wedge angle.

D. Application of ANOVA Technique to Analysis of Extractor Zone Parameters

Table VII summarizes the ANOVA results for the four control factors of the extractor zone. It is observed that the luminance is affected primarily by the taper angle and the shape of the individual optical microstructures. A ray-tracing simulation performed using the optimal factorial combination of A2-B3-C1-D1 found the normal luminance to be 8903 nits. Although this value is higher than any of the luminance values obtained using the original factorial combinations in the orthogonal array (see Table VI), it falls short of the design target of 10 000 nits. In general, the results obtained using the optimal factorial combination identified via an analysis of the S/N ratio data may not in fact be optimal since in performing the experiments, the parameter settings are constrained to the levels predefined in the orthogonal array. Thus, the true optimal solution should be found by systematically modifying the original “optimal” factorial combination (i.e., A2-B3-C1-D1). In practice, this is most easily achieved by incrementally changing the level setting of the most significant factor (i.e., the extractor taper angle in the present case) and observing the corresponding effect on the performance indicator (i.e., the normal luminance). Fig. 7 illustrates the variation in the normal luminance as the taper angle is incrementally increased from 40 ~ 47°. It can be seen that the maximum luminance value is obtained when the taper angle is specified as 45°. Therefore, the true optimal design parameters for the extractor zone of the backlight unit are determined to be as follows: A2 (Extractor shape: Prism), B* (Extractor taper angle: 45°), C1 (Extractor dimension: 0.2 mm), and D1 (Light guide wedge angle: 0°).

Fig. 8(a) and (b) presents the simulation results obtained for the distributions of the normal luminance and color difference, respectively, when the design parameters for the color-mixing zone and extractor zone are all assigned their true optimal

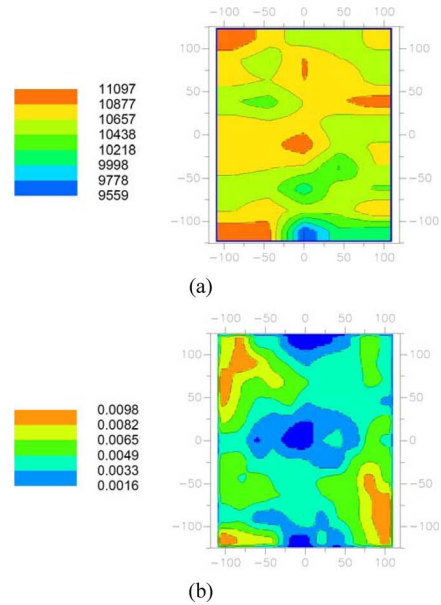


Fig. 8. Spatial distribution of: (a) normal luminance and (b) color difference of emitting surface under optimal design conditions.

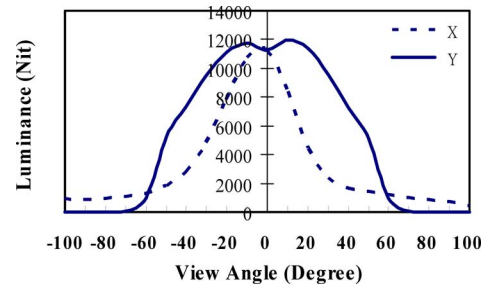


Fig. 9. Angular luminance distributions of optimal backlight system in X- and Y-axis directions.

values. (Note that the input flux is assumed to be 1501 lm.) From a statistical analysis of Fig. 8(a), the uniformity is found to be 85%, while in Fig. 8(b), the color difference is found to be less than 0.01. Furthermore, the maximum luminance in the normal direction is estimated to be 10675 nits. Fig. 9 illustrates the variation of the luminance in the X- and Y-axis directions as a function of the viewing angle. The results confirm that the optimized light guide with prism-shape microstructures constrains the emitted light in the X-direction and therefore causes the light to be emitted in a direction normal to the LCD panel. Most existing large-scale backlight units require the use of two BEFs for LCD applications. However, the effect of the optimized prism-shape microstructures in confining the direction of the emitted light to the normal direction suggests that the two BEFs can be replaced by a single BEF and a diffuser.

IV. CONCLUSION

This study has utilized the Taguchi robust engineering method to optimize the design parameters of an edge-lit backlight unit for wide color gamut LCD displays. The optimization experiments have focused specifically on the correlation between the design parameters and the color-difference, optical efficiency and luminance of the backlight unit. The results have

shown that the optical efficiency and color mixing performance of the backlight unit are governed principally by the reflector design/LED arrangement and the length of the color-mixing zone, respectively. Ray-tracing simulations have shown that the optimized color-mixing zone yields a color difference of just 0.01 and an optical efficiency of 85%. In designing the extractor zone of the backlight unit, the results have revealed that the luminance of the light emitted in the normal direction to the LCD panel is determined primarily by the taper angle of the extractors. Specifically, it has been shown that the luminance increases with an increasing taper angle and attains a maximum value at an angle of 45°. Overall, the results presented in this study confirm the applicability of the Taguchi method to the optimal backlight design problem and provide a blueprint for an edge-lit backlight unit compatible with the requirements of the latest generation of energy-efficient, wide color gamut, large-size LCD display units.

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