LED-Based Projection Systems

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***Abstract*—A novel design methodology for LED-array-based projection displays has been developed. By combining etendue limitation, system intensity, and efficiency requirements, a novel parameter space is proposed. Using this parameter space, LED lens-array and compound parabolic concentrator (CPC)-array illumination systems have been designed. A 1000-lm LED light source is built. Based on these lens-array and CPC-array illuminators, several LED-based liquid crystal on silicon (LCOS) projection systems are suggested. Among them, a one-panel LCOS projection system is proposed and tested. The method discussed here should be useful in the design of LED-array illumination systems for projectors in general.**

***Index Terms*—LED arrays, projectors.**

I. Introduction

THE system performance of a light-valve projector is very much dependent on the characteristics of the illumination system, which includes the projection lamp and its associated optics (mainly the light collection system). A number of the illumination system characteristics can have significant effects on the performance of the projection system. Among these are: lamp power, lamp efficacy, lamp spectrum, and illumination system etendue (or F/#). Other factors, such as lamp lifetime and warm-up time, can also influence the quality of the projector.

Currently, there are two major types of projection lamps used for light-valve projection systems: tungsten–halogen lamps and high-intensity discharge (HID) lamps that include metal–halide lamps, UHP lamps, and xenon lamps [1]. Tungsten–halogen lamps are incandescent lamps with halogen atoms incorporated in the gaseous fill surrounding the filament. Light is emitted from the tungsten filament at around 2800 K to 3200 K. The advantages of these lamps are radiant cooling and low cost (only 0.0005 $/lumen). The disadvantages are low efficiency (15 lm/W) and short lifetime. Also, the fundamental drawback is that it cannot achieve daylight color (color temperature 6500 K) due to the lack of blue light in the spectrum. Thus, these lamps are not used in high-performance high-brightness projection systems. The HID lamp, also known as the arc lamp, consists of a sealed envelope containing a high-pressure gas and two electrodes. The fill gas can be xenon. A liquid such as mercury or a solid such as metal–halide salt is usually added to increase the efficiency. These lamps have very high efficiency (100 lm/W), and the correlated color temperature (CCT) can be as high as 8500 K. The major drawbacks are that they are quite expensive and they produce strong UV/IR emissions. As well, mercury-containing lamps are environmentally unsuitable. Arc lamps are also dangerous as the glass envelope and electrodes can break easily. Despite these drawbacks, arc lamps are used widely in high-brightness projection systems.

As the projection market is increasing, alternative light sources are being explored. There is also a demand for portable low-cost projection systems which do not require very high brightness. Optical performance, portability, and low cost are crucial. HID lamps can provide good optical performance, but they are very expensive and not portable. Tungsten–halogen lamps satisfy the requirement on the cost, but the luminous efficiency and the color-rending ability are unacceptable for most applications. Thus, a novel illumination system needs to be developed for projection systems to satisfy all requirements: low cost, good color rendering, high luminous efficiency, and long lifetime.

Light-emitting diode (LED) technology is ideally suited for these applications [2]–[4]. It has the advantages of excellent color gamut (> 95%NTSC), long lifetime (> 50 K·h), high brightness (> 10 K·nit), and ease of control and is environmentally friendly. The controllability leads to novel ideas such as blinking light source and field sequential color. The continuously improved efficiency makes it one of the best candidates for illumination systems [4]. For the case of projection light sources, generally an LED array has to be used. There have been proposals of single-chip LED projectors as well as LED arrays for high luminous projectors with 400-lm output [2], [3]. For such LED light sources, details, such as illumination optics and LED packaging for heat dissipation, have to be investigated thoroughly.

In this paper, we shall first develop a novel method on LED array optical design for projection systems. Based on this method, the LED lens-array and compound parabolic concentrator (CPC)-array illumination system will be designed and developed, respectively. The package for the LED array will be also studied. Then, several possible architectures on LED-based liquid crystal on silicon (LCOS) projection systems will be suggested. As an illustration, a one-panel LCOS system will be tested experimentally, and the performance will be reported.

II. Optics of LED Arrays

The fundamental questions (or requirements) in any illumination system are: etendue or F/# of the light source, light flux needed, and the acceptable light efficiency. The solution to the first requirement is given by the etendue limit [1]. If the area of the LED light source is A_{LED} with the averaging emitting solid angle of Ω_{LED}, the etendue (E_{LED}) of this light source can be written as

$$E_{\mathrm{LED}} = A_{\mathrm{LED}}\Omega_{\mathrm{LED}} \quad (1)$$

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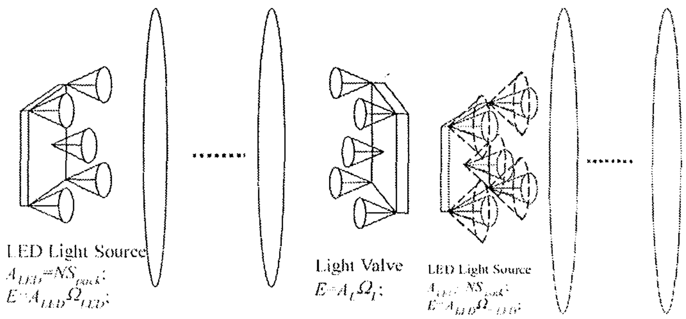

Fig. 1. Illumination system with 100% and η_{LED} light utilization efficiency.

The image of this light source through the light collection system at the position of the light valve has the total area of A_{I} and an averaging solid angle of Ω_I. For any optical systems, the etendue never decreases. Thus, the size of the light source is given by

$$A_{\mathrm{LED}} \leq \frac{\Omega_I}{\Omega_{\mathrm{LED}}} A_I. \tag{2}$$

For the desired light collection system, as shown in Fig. 1(a), the total light flux of the LED source is completely projected onto the light valve with the requested F/#, that is, the area of A_I is equal to the area of the light valve A_L. As well, the solid angle Ω_I should be equal to or less than the requested solid angle Ω_L for the light valve. Since the LED source should be compact, and the total area of LED light source is given, then

$$A_{\mathrm{LED}} = N \bullet A_{\mathrm{pack}} \tag{3}$$

where N is the number of LEDs in the array and A_{pack} is the area of each LED package. Thus, the LED maximum number N is given by

$$N \leq \frac{\Omega_I}{\Omega_{\mathrm{LED}}} \frac{A_I}{A_{\mathrm{pack}}} \leq \frac{\Omega_L}{\Omega_{\mathrm{LED}}} \frac{A_L}{A_{\mathrm{pack}}}. \tag{4}$$

For the case described by (4), the illumination system has the highest light utilization efficiency (100%), which means all of the light from the light source can be utilized.

If the LED number is increased, the total flux of the LED source will increase as well. However, at the same time, the light utilization efficiency will decrease since the etendue will be larger. The question is whether the flux of the light that can enter the light engine with the desired F/# also increases.

Assume that light flux Φ_{LED} can enter the light engine and be utilized completely, as shown in Fig. 1(b). This flux Φ_{LED} is contained in a solid angle of $\Omega_{\%\mathrm{LED}}$. The light utilization efficiency is

$$\eta_{\mathrm{LED}} = \frac{\Phi_{\mathrm{LED}}}{\Phi_{\mathrm{LED-total}}} \tag{5}$$

where $\Phi_{\mathrm{LED-total}}$ is the total flux of the single LED. Then, the maximum LED number N for the illumination system with the utilization efficiency of η_{LED} is given by

which is similar to (4) except for the new solid angle $\Omega_{\%\mathrm{LED}}$. The maximum usable light flux F is

$$\begin{aligned} F &\leq \frac{\Omega_L}{\Omega_{\%\mathrm{LED}}} \frac{A_L}{A_{\mathrm{pack}}} \eta_{\mathrm{LED}} \Phi_{\mathrm{LED-total}} \\ &= \left(\frac{\eta_{\mathrm{LED}}}{\Omega_{\%\mathrm{LED}} A_{\mathrm{pack}}} \right) \Omega_L A_L \Phi_{\mathrm{LED-total}}. \end{aligned} \tag{7}$$

It should be noted that the calculations above are based on the estimated etendue given by (1). The more accurate etendue calculation [1] is given by

$$E = \int \int \cos\theta d\Omega dA. \tag{8}$$

This calculation strongly depends on each specified optical system. Generally, no analytical equation can be derived. The analysis based on the accurate etendue calculation is quite complicated and sometimes impossible. Thus, it only can be done qualitatively. The results of our estimated calculations can be very good initial designs for the LED light sources. This will be verified later.

Note that the etendue does not refer to the light intensity within the distribution of interest: it only refers to the distribution's geometric boundaries. Thus, the second and third requirements in the illumination design are related to flux and efficiency. If the efficiency of the system light engine is η_{LE}, then the maximum final output $\Phi_{\mathrm{on-screen}}$ on the screen will be

$$\begin{aligned} \Phi_{\mathrm{on-screen}} &= \eta_{\mathrm{LE}} F \\ &= \eta_{\mathrm{LE}} \bullet \left(\frac{\eta_{\mathrm{LED}}}{\Omega_{\%\mathrm{LED}} A_{\mathrm{pack}}} \right) \\ &\quad \times \Omega_L A_L \Phi_{\mathrm{LED-total}}. \end{aligned} \tag{9}$$

If the input power of each LED is 1 W, then the system luminous efficiency γ is

$$\gamma = \frac{\Phi_{\mathrm{on-screen}}}{N \cdot 1} = \Phi_{\mathrm{LED-total}} \eta_{\mathrm{LED}} \eta_{\mathrm{LE}}. \tag{10}$$

Rewriting (9) and (10) gives

$$\frac{\Phi_{\mathrm{on-screen}}}{\Phi_{\mathrm{LED-total}}} = \left(\frac{\eta_{\mathrm{LED}}}{\Omega_{\%\mathrm{LED}} A_{\mathrm{pack}}} \right) \Omega_L A_L \eta_{\mathrm{LE}} \tag{11}$$

$$\eta_{\mathrm{LED}} = \frac{\gamma}{\Phi_{\mathrm{LED-total}} \eta_{\mathrm{LE}}}. \tag{12}$$

Equations (11) and (12) are the key rules for the LED-array based illumination system design. The factors $\Omega_L A_L, \eta_{\mathrm{LE}}$, and $\Phi_{\mathrm{LED-total}}$ depend on the system requirements (panel size, F/#, and light engine efficiency) as well as the LED die itself ($\Phi_{\mathrm{LED-total}}$), while $\eta_{\mathrm{LED}}/A_{\mathrm{pack}}\Omega_{\%\mathrm{LED}}$ is dependent on the LED optical performance and design.

Based on these rules, any LED array designs can be carried out in a parameter space. The factor $((\eta_{\mathrm{LED}})/(\Omega_{\%\mathrm{LED}} A_{\mathrm{pack}}))\Omega_L A_L \eta_{\mathrm{LE}}$ for different LED optical designs is plotted as a function of the LED light collection efficiency η_{LED}. $(\Phi_{\mathrm{on-screen}})/(\Phi_{\mathrm{LED-total}})$ and $(\gamma)/(\Phi_{\mathrm{LED-total}}\eta_{\mathrm{LE}})$ are calculated according to the system requirements, and they give the minimum requirements or the boundaries in the param-

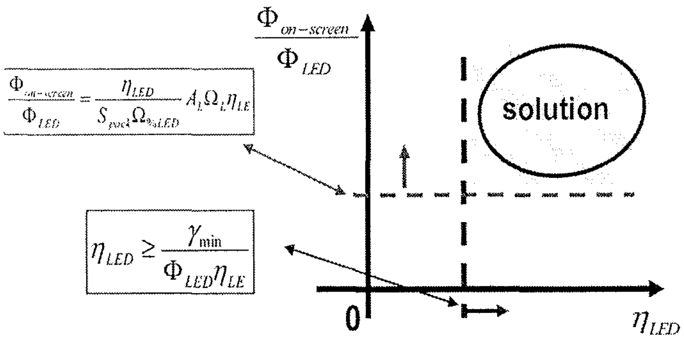

Fig. 2. Parameter space with minimum requirements or boundaries.

TABLE I
BOUNDARIES FOR DIFFERENT $\Phi_{on-screen}$, $\Phi_{LED-total}$ WITH 8% η_{LE}

η_{LE}	8%			
$\Phi_{on-screen}$	20 lm		40 lm	
$\Phi_{LED-total}$	30 lm	50 lm	50 lm	80 lm
$\frac{\Phi_{on-screen}}{\Phi_{LED-total}}$	0.66	0.4	0.8	0.5
$\frac{\gamma}{\Phi_{LED-total}\eta_{LE}}$	0.42γ	0.25γ	0.25γ	0.16γ

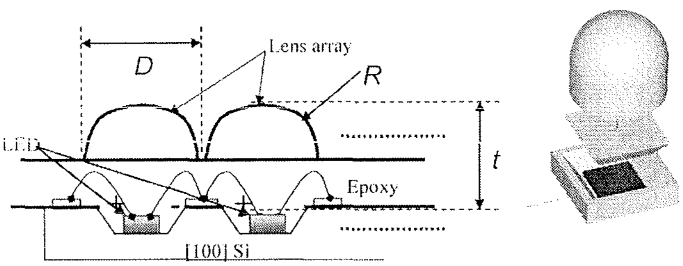

Fig. 3. Structure of LED lens array.

engine efficiency η_{LE} of 8% for different required final output $\Phi_{on-screen}$, the total flux $\Phi_{LED-total}$ of the single LED.

The objective of the LED illumination design is to find the LED optical package that satisfies these two minimum requirements. In this paper, the LED lens-array and CPC-array will be designed according to these laws.

The structure of the LED lens-array is shown in Fig. 3. The 1-W 1-mm^2 LED dies are placed inside the wet-etched [100] Si V-grooves. On top of the LED-groove substrate, the lens array is then fabricated after wire bonding of the LED dies. The fabrication method for the lens array is a so-called "molding" method, which is originally developed for the micro-lens array used in the organic LEDs [5]. There are four physical parameters in the LED lens-array structure: the aperture (D), the radius (R), and the thickness (t) and refractive index (n) of the materials, as shown in Fig. 3. By varying these four parameters of the lens-array, $((\eta_{LED})/(\Omega_{\%LED}A_{pack}))\Omega_L A_L \eta_{LE}$ can be plotted as a function of the LED light collection efficiency η_{LED}. Take a 1-mm radius (R) silicone-based lens array Thus, $D_{max} = 2R$ when $t \geq R$. Thus, the only variable is the lens-array thickness (t). For each t, $(\eta_{LED})/(\Omega_{\%LED}A_{pack})$ can be easily calculated with commercial optical design software, such as TracePro, ASAP, or LightTools. Fig. 4 shows $((\eta_{LED})/(\Omega_{\%LED}A_{pack}))\Omega_L A_L \eta_{LE}$ versus η_{LED} parameter space as a function of the lens-array thickness t with different R (or D). Fig. 5 shows the maximum LED number N based on (6) versus η_{LED} parameter space as a function of the lens-array thickness t with different R (or (D). The light valve used here is 0.87-in LCOS panel with F/2 optics, and the light engine efficiency is 8%.

According to the minimum requirements of 8% efficient LCOS systems listed in Table I, the boundaries in the parameter space are: 1) the flux boundary $(\Phi_{on-screen})/(\Phi_{LED-total}) \geq 0.66$ and 2) the efficiency boundary $\eta_{LED} = (\gamma)/(\Phi_{LED-total}\eta_{LE}) \geq 0.42$ if the required final output is 20 lm with the system luminous efficiency of 1 lm/W and assuming 30 lm/W LED dies are used. Thus, the design solution in the parameter space should be above these two boundary planes. From Fig. 4, then the proper t and $R(D)$ can be obtained (physical parameters of each LED optical structure). Once these parameters are known (D, R, t and η_{LED}), from Fig. 5, the number of LED N can be found. For the lens-array solution, in order to achieve the final performance of 20-40 lm with the system luminous efficiency of 0.6–1.4 lm/W, 15–40 LEDs with 50 lm/LED will have to be used. The questions on LED illumination design, including the structure of the lens arrays (D, R, t), number of LEDs, and the light collection efficiency η_{LED}, can be obtained in the parameter space.

The problem for LED lens-array method is that it needs many LEDs to achieve a large final output. This will result in a low system luminous efficiency, if the light engine efficiency is not high enough. The reason for this is that the lens array is not a perfect optical component for light collection.

In order to solve this problem, a solid CPC-array has been designed. The circular CPC was developed recently in an LED illumination system [6]. However, because the LED and the light valve (TFT, LCOS, and DLP) are all rectangular, the CPC should also be rectangular in order to obtain a high light collection efficiency η_{LED}. Our rectangular CPC and LED CPC-array structures (2 × 3) are shown in Fig. 6. There are five shape parameters for this CPC: focal length f of the parabolic shape, tilt angle α of the parabolic axis, the front length FL, the back length BL, and focal shift DF. From a design point of view, the output diameter (D_{out}) and the input diameter (D_{in}) of a CPC is more important, and both are functions of the five shape parameters. The input diameter (D_{in}) is limited by the size of LED dies and packaging of the LED dies. Thus, the main design parameters will be D_{out} and the total length (LF-LB).

Similar to the lens-array design, by varying these five parameters of the CPC, the design parameters (D_{out} and LF-LB) can be calculated. For different design parameters, $((\eta_{LED})/(\Omega_{\%LED}A_{pack}))\Omega_L A_L \eta_{LE}$ can be plotted as a function of the LED light collection efficiency η_{LED}. This result is shown in Fig. 7 as a function of D_{out} of the CPC. Fig. 8 shows

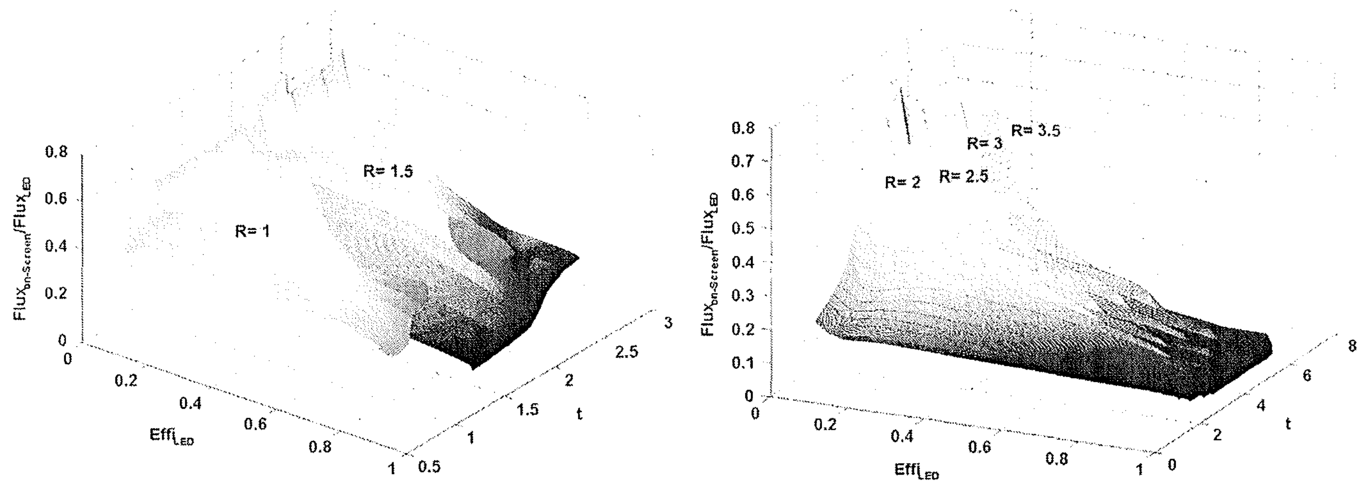

Fig. 4. $((\eta_{\mathrm{LED}})/(\Omega_{\%_{\mathrm{LED}}} A_{\mathrm{pack}}))\Omega_L A_L \eta_{\mathrm{LE}}$ versus η_{LED} parameter space for the lens array.

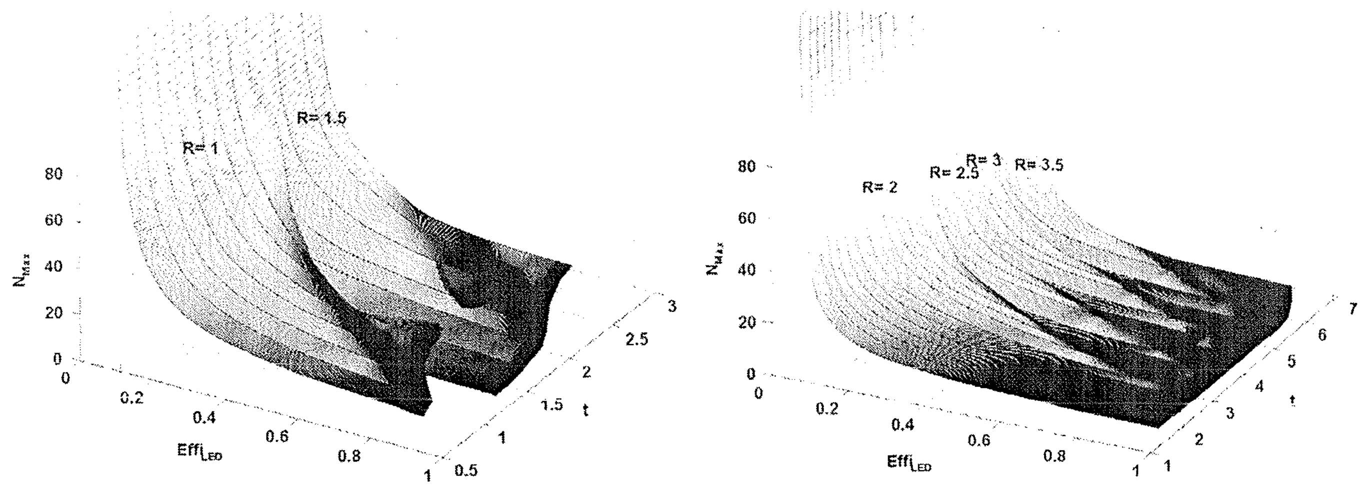

Fig. 5. Maximum LED number N versus η_{LED} parameter space for the lens array.

Compared with the lens-array parameter space, for the same boundary (e.g., $(\Phi_{\mathrm{on-screen}})/(\Phi_{\mathrm{LED-total}}) \geq 0.66; \eta_{\mathrm{LED}} = (\gamma)/(\Phi_{\mathrm{LED-total}}\eta_{\mathrm{LE}}) \geq 0.42$), the CPC system has solutions with high system luminous efficiency. For the same engine system and a final output of 20 lm, the CPC needs only six LEDs with an overall system luminous efficiency of > 3 lm/W.

III. LED Illumination System

A. Packaging

After the optical design of the LED array is done, the LED illumination system can be packaged. Although the lens-array system has lower efficiency than the CPC one, we still use it in our investigation due to the ease of fabrication. According to the lens-array design, the LED has to be packaged very close to each other. The most important issue for this ultracompact LED light source is heat dissipation. A 1-mm^2 LED dissipating 1 W corresponds to 100 W/cm^2 of heat flux, which is twice the amount of the heat flux generated in a conventional microprocessor chip. Nowadays, flip-chip technology (FCT) is one of the best solutions for heat dissipation. It can be used in our package.

We also developed a normal package for the LED lens array. The idea is that, using a silicon wafer as the substrate, heat can be dissipated efficiently due to its high thermal conductivity. The LED dies are placed on the bottom of the wet-etched [100] silicon V-shape groove as shown in Fig. 3. The surfaces of these V-shape grooves are coated with a metal such as aluminum, which serves as a mirror. The shape of the V-shape groove is important optically. Then, the lens array with the desired dimension based on our design is formed on top of the optimal LED-groove substrate. The LED dies are mounted on the V-groove substrate by using thermally conductive epoxy. The same epoxy is also used to glue the silicon substrate onto the aluminum heat sink.

The heat flow through the conducting layers attached in parallel or series can be analyzed in the equivalent thermal circuit [7]. Thermal conductivities of the various materials used in our package must be maximized. Of particular interest are the various interface materials, which constitute a large portion of the

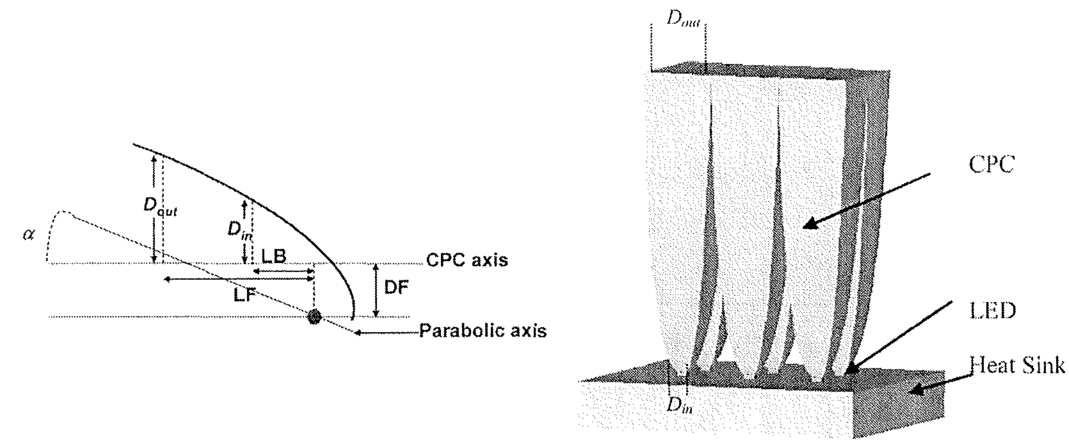

Fig. 6. Rectangular CPC and LED CPC-array structures.

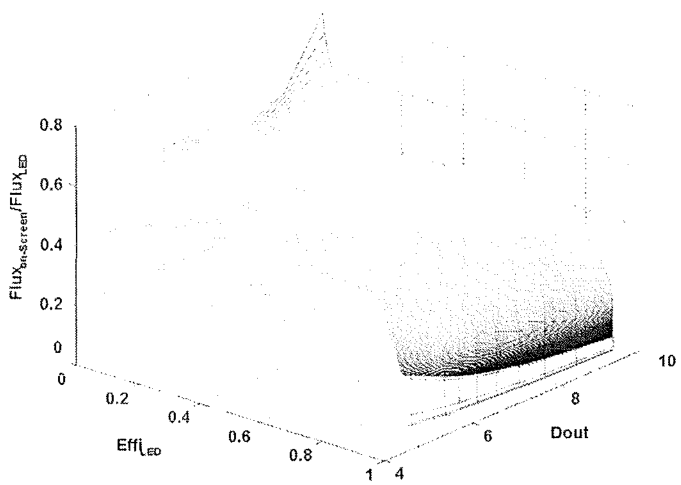

Fig. 7. $((\eta_{\rm LED})/(\Omega_{\%\rm LED}A_{\rm pack}))\Omega_L A_L \eta_{\rm LE}$ versus $\eta_{\rm LED}$ parameter space for the CPC array.

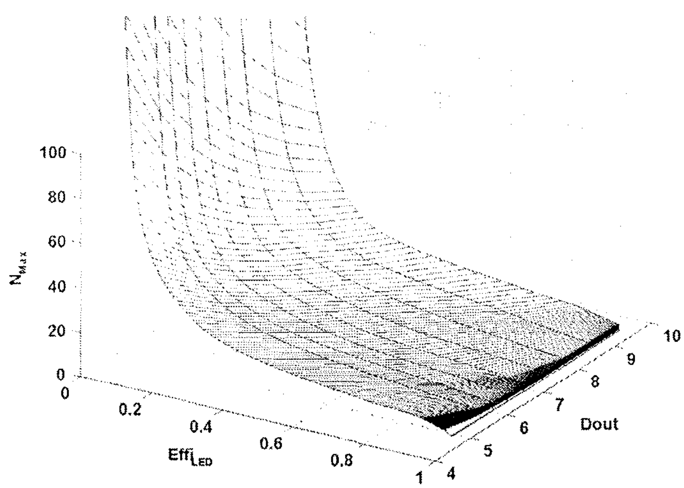

Fig. 8. Maximum LED number N versus $\eta_{\rm LED}$ parameter space for the CPC array.

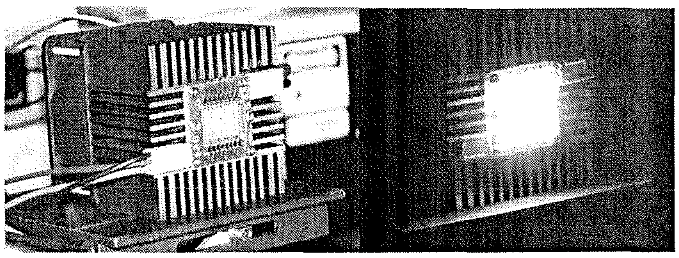

Fig. 9. LED lens-array light source package with 40 1-W LEDs.

LED lens-array package is only limited by the LED sapphire substrate, which is 30 °C/W. The significant decrease in thermal resistance (compared with the traditional 5-mm package T-1 and T-1 3/4, $R_{\rm thjp} > 200$°C/W) allows high-current-density operation.

It is estimated that the maximum junction temperature for a 1-mm^2 LED die is around 120 °C. The measured package temperature is $<$ 40 °C for 40 1-W LEDs packaged at the area of 160 mm^2. Thus, the permissible dissipation of our package is approximately 2 W. Fig. 9 shows the LED lens-array light source with 40 (8 $\times$ 5) 1-W LEDs (blue LEDs plus yellow phosphor) packaged at the area of 160 mm^2. The bare LED chips are from Epistar Corporation, with 27–30 lm/LED. The total output of this light source is 1000–1100-lm white light at a driving current of 350 mA for each LED. The R, G, and B LEDs are also tested on our package, and similar performance is obtained.

For the CPC array solution, the LED package is much easier since less LEDs are used and LEDs are placed several millimeters ($\sim$ 7 mm in our design) away from each other. Thus, both FCT and our normal package can be used, and the heat dissipation will not be a problem. We also package the CPC system with a 2$\times$3 LED array.

B. Polarization Conversion

If the LED illumination system is employed for the projection system based on a liquid crystal light valve, polarization conversion is needed [8]–[12]. The simple reflective polarizer and the

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