Using a fly's eye integrator in efficient illumination engines with multiple light-emitting diode light sources

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Abstract. High brightness light emitting diodes (LEDs) become a serious alternative for ultrahigh performance lamps in projection displays. We focus on the illumination part of a LED projection engine. We discuss the problem of using several LED light sources for each primary color. In critical applications, the use of several light sources for each color has important benefits. It increases the possible light output to the screen and makes it possible to design a system that is tolerant for failures of one of the LEDs. Therefore, we need an optical system that is both efficient and is able to produce a uniform light beam if one of the LEDs fails. We show that our illumination engine using a fly's eye integrator meets these requirements, using ray-tracing simulations of the engine. An efficient optimization method based on the simplex method [R. J. Koshel, Opt. Lett. 30, 649–651 (2005)] was developed to design the LED collimation reflective device with collection efficiencies up to 95%. The lens systems in the engine were designed with the same method. This results in a total system efficiency of 77%. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2727313]

Subject terms: LED; illumination; projection display; optimization; nonimaging optics.

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1 Introduction

With the new generation of high-brightness light-emitting diodes (LEDs), it is possible to use this light source in applications where both high luminous flux and high luminance are important. One such application is the use of these light sources in a projection display. LEDs are small light sources with a relatively narrow spectral emission band and a low operating voltage, which make them ideal light sources for compact projectors. Other benefits of LEDs include the possibility for an extended color gamut and a large dimming ratio. A drawback of LEDs, in comparison with ultra high performance (UHP) lamps, is the still-limited light output and luminance of LEDs. This means that one needs a very efficient illumination system to prevent unnecessary losses. In a LED-based projection display architecture, at least one high-brightness LED module is used for each main color (red, green, blue). In this paper, we discuss the problem of using multiple LEDs for one or more colors. This increases the possible light output to the screen.

The light sources that are used in this paper are the OSTAR high-brightness LED modules from OSRAM semiconductors with four square-shaped dyes that emit their light directly in air, thus without any dome.1 This makes it easier to design efficient collimation optics for these LEDs. These OSTAR LED modules are available in the three main colors (blue, red, and green).

Only the illumination part of the optical system will be discussed, we will not go into detail on the projector architecture or on the chosen light valve. The illumination engine can be used with different light valve technologies. All cited results are based on ray tracing through a model of the illumination engine. Fresnel reflection losses were not taken into account, because these depend very much on the coatings that are chosen for the optical components. A 100% reflective coating is assumed on the sides of the hollow LED collimator.

The ray-tracing software we use in this contribution is the Advanced Systems Analysis Program (ASAP) from Breault, Inc.2 This is a very flexible and powerful nonsequential ray-tracing software package. Its script-driven interface and batch mode permits collaboration with other software packages. We use the optimization routines of MATLAB to optimize ASAP designs. Other ASAP features include targets and sources with practically any angular or spatial distribution and the implementation of free-form surfaces. These features are vital for our optimization method. For the optimization part in MATLAB, we use the downhill simplex method as it is implemented in MATLAB.3,4

Transforming the light distribution of the sources into a sufficient uniform beam with a certain spatial and angular extent is the key problem we deal with. The use of several light sources for the same color makes this problem even more complicated. A failure of one of the LEDs or brightness differences between the LED light sources must not lead to visible nonuniformities on the screen. Each LED should therefore illuminate the imager completely and uni-
formly. In general, one has two choices for the integrator part of the illumination engine. A first choice is the fly’s eye integrator using two rectangular lenslet arrays. A second choice is a (tapered) light pipe. We found that the requirement for a sufficient uniformity for different LEDs leads to very long light pipes. Therefore, in this paper, we investigate fly’s eye integrators.

The study of the transformation of light bundles into bundles with other spatial and angular distribution is often investigated in the context of nonimaging fly’s eye integrators. This is because the goal is not to make a good image of an object. The light distribution is being guided and transformed through the system in an efficient way.

The étendue of a light bundle in air is given by its integral over angular and positional extent,

$$E = \int dL dM dxdy,$$  \hspace{1cm} \hspace{0.5cm} (1)

where $L$ and $M$ are the directional cosines with respect to the $x$ and $y$ axes. The phase-space conservation law, or étendue conservation law, states that in an optical system without losses the étendue is conserved. At each position in the system, the étendue of the light bundle is the same. The challenge is to produce at a certain target a light bundle without “holes” and this with as high as possible optical efficiency. In that case, the light valve is filled completely both in position and direction and the maximum amount of light is captured onto the target.

In this paper, we investigate the case where the étendue of one LED only is not sufficient to fill the acceptance étendue of the light valve, and it is advantageous to use several LEDs for one color. A fly’s eye integrator is used. We develop a flexible optimization method to design efficient optical systems for illumination purposes.

### 2 Optimizing Nonimaging Systems

Nonimaging systems are optical systems where the goal is to obtain a maximal transfer of light between the source with a certain light distribution and a target with a certain positional and angular acceptance light distribution. A detailed description of the differences between an imaging and a nonimaging approach in optical design is given in Ref. 6. In this section, we develop an optimization method for these kinds of optical systems. This method will be used extensively in our multi-LED design.

To optimize an optical system, we describe the system in terms of a set of free parameters. For example, in a lens system, these parameters would be the radii of curvature of the lenses and the distance between them. These parameters define the structure of the optical system. For the system, a source and a target are defined. The source is a set of rays that will be traced through the system. The target is one or a combination of surfaces in the system with a certain acceptance directional distribution. In an optimization step, ASAP traces the rays of the source through the system defined by a particular set of parameters calculated in MATLAB. ASAP calculates the merit function. Generally, this is the ray flux on the target within the desired directional acceptance distribution. This merit function is used by a MATLAB function as feedback to calculate a new parameter set. This is repeated until a global maximum for the merit function is found.

As a first example of this approach, we consider a collimator for our light source. This is a classical example of a nonimaging system. We use square-shaped reflectors where the smallest square matches the dimensions of the dye. Figure 1(a) depicts a reflective collimator on a OSRAM LED module. A standard solution for the collimation of light sources is the compound parabolic concentrator (CPC). Square CPCs are discussed by M. Krijn et al., and more, generally, the use of square-shaped reflectors for the redistribution of light is discussed in Ref. 9. The transformation between a standard axisymmetrical CPC and a square CPC is not straightforward. The length is a parameter that can be chosen.

We will optimize this optical component with our general-purpose method. The side profiles of our collector are conical. Optimized reflectors were used as a collimator for OSRAM LEDs in Ref. 10. Kudaev et al. optimized for an optimal uniformity of the light distribution at the target. We will optimize them for optimal light transfer.

The sides of the reflector have conical profiles. A conical curve is described by only two parameters if two points of the curve are already known. The parameters are the coordinates of the control point $C$ [Fig. 1(b)]. At the LED side, the square input aperture has the same size as the light emitting area of the LED ($a' = 1.05$). A collimation angle is chosen ($\theta$) and the size of the exit aperture can be calculated from étendue conservation [Eq. (1)] and the size of the die.

$$a = \frac{a' \sin(\theta)}{1}. \hspace{1cm} \hspace{0.5cm} \hspace{0.5cm} (2)$$

The length of the collector ($L$) is not considered as a free parameter in the design. We optimize the system for different lengths and chose the length with the minimal required performance. In this example, we designed a LED collimator for an output angle of 20 deg. In Fig. 2, the optimized efficiency of the collector (the merit function) is shown as a function of the length of the collector. This performance is
compared to the performance of square CPCs. The efficiency is the amount of light that is traced through the system and falls on the exit aperture of the reflector (the target) and within the angular extent that is prescribed by the étendue conservation law. We see that a square CPC is not the optimal solution to this problem, and that with our optimization method, we can obtain higher collection efficiencies.

Also, lens systems, which are normally described in imaging terms, can also be treated as nonimaging lens systems. The relay lens system in Fig. 3 was optimized using our nonimaging technique. In our system, it transforms the uniform distribution at infinity after the fly’s eye integrator onto the light valve.

A first-order solution to this problem can be calculated using ABCD matrices. The paraxial transfer matrix $\mathbf{M}$ of this optical system is

$$
\mathbf{M} = \begin{bmatrix} F & 1 \\ -1/F & 0 \end{bmatrix} \begin{bmatrix} F & 1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & F \\ -1/F & 0 \end{bmatrix}.
$$

(3)

Starting from the paraxial approximation, we optimize the parameters of the system for optimal flux transfer from the source to the target. Again, the parameters are chosen by a MATLAB function that uses data from the previous ASAP calculations.

We do realize that it is possible to optimize such a lens system using imaging techniques by minimizing the geometrical aberrations. Our approach, however, has more possibilities for illumination systems and is more flexible. In the ray tracing of the system, we can implement real anti-reflecting coatings or several angular or transversal misalignments for optimizing the system tolerance. These effects are than implemented directly in the merit function of the system. The merit function is the flux of rays that are traced through the system and fall on a target within a certain acceptance directional distribution. The merit function can be composed of the (weighted) sum of such fluxes of different systems. The systems in the merit function can differ because we want to implement spectrally dependent phenomena or want to use several misalignments for a certain component. The possibilities of the optimization method to include tolerance studies or dispersion effects is something we plan to investigate.

### 3 Fly’s Eye Integrators

A fly’s eye integrator consists of a pair of identical arrays of rectangular lenslets [Figs. 4(a) and 4(b)] and a relay lens system. The goal of the lenslet integrator is to transform a nonuniform beam into a uniform one in an efficient way.

The lenslet arrays are placed in each other’s focal plane. A lenslet of the first array depicts the angular distribution of the incoming light bundle on the footprint of its opponent in the second array. A lenslet of the second array images its opponent in the first array at infinity. The uniform image on the imager consists of the sum of the light distributions at infinity of each individual lens pair redirected by a relay lens system to the imager. The incoming directional distribution is imaged on the rectangular footprint of a lenslet. This means that the integrator has a certain rectangular directional acceptance distribution. The extent of this rectangular angular distribution depends on the radius of curvature of the lenslets (in other words, their focal length) and the dimensions of the lenslets. Only light that falls on the first array within the angular acceptance of the array
will reach the light valve. Light beyond this directional distribution will lead to cross talk between the lenslets and will not be displayed on the light valve. The fly’s eye integrator can be very étendue efficient. When the illumination of the device provides a light distribution with the proper rectangular directional distribution, the étendue at the light valve will be filled completely.

Schreiber et al. discuss the lenslet integrator in imaging terms. Distortion and lateral color changes are discussed. The latter were found to be less important. In our work, aberrations due to color spectra of the LEDs were not taken into account.

In the lenslet array integrator, a pair of two opposite lenslets is an example of an area-to-angle converting lens system (2F processor). The incoming light bundle at a single lenslet is rectangular in both angular and positional space. This is a system we can manage with our optimization method. The source is a light beam with a certain rectangular directional distribution falling on the first lenslet. The target is the back plane of the second lenslet with the same rectangular directional acceptance distribution. The first and second lenslets have the same dimensions, so the system is optimized for optimal étendue conversion. The distance between the lenslets and the radius of curvature of the lenslets are the free parameters in the system.

The radius of curvature of the lenslets is an important specification. The more the lenslets in the array are curved, the less optically efficient the integrator is. In imaging optics, we would say that we have aberrations. This decreases the uniformity on the imager. However, the length of the optical system will increase if we use lenslets with a large radius of curvature. The focal length of the lenses increases with less curved lenslets, and the relay lens system should have a higher focal length for less curved lenslets.

In Fig. 5, we see how efficiency and uniformity vary as a function of the size of the incoming directional distribution.

\[ \text{Efficiency} \quad \text{Uniformity} \]

\end{figure}

Fig. 5 Efficiency and uniformity as a function of the size of the incoming directional distribution.

4 An Efficient Illumination System

Figure 6 gives an overview of the optical system we studied in detail. The source consists of six OSTAR LEDs in a two-by-three configuration. The light is collected by an efficient optimized reflective collector as we described in Sec. 2. In this configuration, the aspect ratio of the source approaches the 4:3 aspect ratio of the light valve. A first lens system consisting of two lenses is used to transform the rectangular positional distribution into an angular distribution. This is the shortest implementation of a 2F processor.

The two lenslet arrays homogenize the incoming light beam and form a uniform rectangular light distribution at infinity. This light distribution is redirected on the light valve by the second lens system, similar to the first one.

In our illumination system, the source (a LED array) shows nonuniformities that we want to hide. A first source of nonuniformities is caused by the fact that we keep some space between the LED collectors. The small étendue difference between the source and the target makes this possible. A CPC with a smaller output surface has a larger output angle and a smaller length. The a we chose for the CPC was 6.65 mm and the length of this CPC was 68 mm. A second kind of nonuniformity occurs due to our requirement that the system should be tolerant for failures of one of the LEDs. An illumination situation where one of the LEDs fails clearly gives an nonuniformity on the source side. In our design, this can be compensated by the other LEDs. Each LED is displayed uniformly on the entire light valve. A third possible source of nonuniformity at the source side is the fact that there is some space between the dyes in a LED module.

Figure 7(a) depicts the incoming angular distribution at the entrance of the integrator, which is an image of the source. Figure 7(b) shows the angular distribution on the light valve. This distribution depends on the number of
lenslets used in the lenslet integrator. The coordinates are the directional cosines with respect to the x and y axes.

Table 1 gives the parameters of the lenslet array used in the simulated system. Reference 5 states that 25 to 80 lenses per array are sufficient for a uniform illumination of the imager. The actual number of lenslets that is chosen for a projection system will depend on the used light valve technology and whether it is or it is not important that the angular distribution of the different LEDs on the light valve should be equal. The more lenslets, the less the angular distributions of the different LEDs on the light valve are shifted toward each other.

The étendue of one OSTAR module is 13.9 mm² sr. We suppose a 1.4-in. pSi LCD light valve and a f/2.3 projection lens and provide a 10% overfill on the light valve. The angle of the light bundle at the light valve can be calculated from the f number. In that way, the étendue of the bundle on the light valve and its overfill can be calculated as 94.6 mm² sr. The étendue of the sources approximately matches the étendue of the target. Losses due to étendue mismatch are minimized. There is a small aspect ratio mismatch because of the conversion between the 2:3 and 3:4 aspect ratio of the light sources and the target light valve, respectively.

In Table 2, we cite the optimized optical efficiency of each part of the final system. We see that the losses can hardly be reduced. The étendue and aspect ratio of source and target were fit to each other and all the optical components are optimized for flux transfer. Supposing that one green OSRAM Ostar module emits 160 lm, this system would deliver a 774-green-lm illumination, and this with conservation of luminance due to our stringent étendue considerations. Note that antireflective and reflective coating losses were not taken into account.

It was not only important to have an optically efficient system, but the uniformity on the screen should also be good. In Table 3, we cite our results based on ray tracing of six million rays through the system. We conclude that the fallout of one of the LEDs will hardly influence the uniformity on the screen. One will see only an intensity drop on the screen if one of the LEDs should fail. This can be corrected by an electronic driving circuit that controls the current through the LEDs. Even the uniformity of a single LED on the light valve is reasonably good.

We conclude that our approach to emphasize optical efficiency does not degrade uniformity. The uniformity of our optical system is excellent, even if the LEDs in our system would have a different optical power. A fallout of one of the LEDs has little influence on the uniformity on the imager.

The length of our system is 220 mm (exclusive reflector), and the width is 40 mm. The reflector is 68-mm long. The dimensions of our system largely depend on the dimensions of the OSTAR modules. Because of the width of such a module (15 mm) (Fig. 1), we have to work with relatively small angles to maintain étendue. For CPC-like systems, such as the used reflector, it is known that these tend to be very long for small angles. Lens systems with small angles (and subsequently larger radii) have larger focal distances. LED modules with a smaller width would lead to a smaller optical system, with low losses or without additional losses.

The illumination system we suggest here is not the only case where our efficient illumination engine would be profitable. In a recent paper, Geißler et al. propose a configuration where two times a 2 × 3-dies Ostar module is used.13

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<th>Table 1 Parameters of the used lenslet array.</th>
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<td>B&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>R/D</td>
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<td>Radius of the array</td>
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<th>Table 2 Efficiency of the different parts of the system.</th>
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<td>Collection efficiency</td>
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<td>First lens system and aspect ratio mismatch</td>
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<td>Lenslet array</td>
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<td>Relay lens system</td>
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<td>Overfill</td>
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<td>Total</td>
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<th>Table 3 Overview of the uniformity on the imager.</th>
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<td>Average/Maximum</td>
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<td>Single LED</td>
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<td>Five LEDs</td>
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<td>Six LEDs</td>
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Fig. 7 (a) Non-uniform incoming directional distribution. (b) Directional distribution on the light valve.
In such a configuration, our illumination design can be used to efficiently display both LED modules uniformly on the light valve.

5 Conclusions
In this contribution, we proposed an illumination system for LED projection systems with multiple LEDs per color. We showed that with a fly’s eye integrator, it becomes possible to display each single LED module uniformly on the screen. This process is very efficient because of the étendue maintaining properties of this illumination system.

The optical components such as relay lenses and LED collimation optics were optimized using a nonimaging approach. We showed that we can design very efficient optics in this way.

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References

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Hugo Thienpont graduated as an electrotechnical engineer in 1984 and received his PhD in applied sciences in 1990, both at the Vrije Universiteit Brussel (VUB), Brussels, Belgium. In 1994, he became a professor of the faculty of applied sciences teaching photonics. In 2000, he became research director of TONA at VUB, and in 2004, he was elected chair of the department. Currently, he is the coordinator of several basic research and networking projects such as the European Network of Excellence on Micro-Optics (NEIO). In addition to academic-oriented research projects, he manages microphotonics-related industrial projects with companies like Barco, Agfa-Gevaert, Tyco, and Umicore. He authored 80 SCI-stated journal papers and more than 250 publications in international conference proceedings. He edited 15 conference proceedings and authored 5 chapters in books. He was an invited speaker at 40 international conferences and is coinventor of 10 patents. Prof. Thienpont was guest editor of several special issues on optical interconnects for Applied Optics and the IEEE Journal of Selected Topics on Quantum Electronics and is general chair of the SPIE Photonics Europe conferences in Strasbourg. In 1999, he received the International Commission for Optics prize ICO’99 and the Ernst Abbe medal from Carl Zeiss. In 2003, he was awarded the title of IEEE LEOS distinguished lecturer. In 2005, he received the SPIE president’s award for dedicated service to the European Community. He is a fellow member of SPIE and a member of EOS, IEEE LEOS, and OSA.