Efficient illumination in LED-based projection systems using lenslet integrators

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ABSTRACT

Illumination systems with lens array integrators for LED-based projection systems are thoroughly investigated. The aim is to develop compact and efficient projection systems with a high image-quality. Different possible illumination configurations for single-panel LCOS projection architectures, are critically evaluated with the use of advanced optical simulations. LED-light collectors which are to be used in combination with the lenslet integrators are also investigated.

Keywords: LED projection, LED collection, illumination system, lens integrator, LCOS, optical simulation

1. INTRODUCTION

The light flux of light emitting diodes (LED’s) has improved consistently since their invention. This progress makes it recently interesting to use these devices as light sources for projection applications. LEDs are small light sources with a narrow spectral emission band and a low operating voltage, which makes them the ideal light sources for compact projection systems. Several prototypes of such systems have already been reported in the literature.

Although LED-based projection systems have other possible interesting features: an extended color-gamut, long life time, more robust; especially the possibility to develop compact projection systems is the main driving force for the research of such projection systems. This is related with the fact that only a limited light output is possible for LED-projectors with today’s LED’s. If we want to construct a LED-based projection system with a good image-quality it is important that the images on the screen are as bright as possible and uniform. To obtain a rectangular uniform illumination of the light valve(s) there are two main types of integrators that are used in projection systems: lenslet integrators and rod integrators. Rod integrators can be used in combination with transmissive LCD micro-displays to construct a compact projection system, but in combination with reflective light valves (liquid crystal on silicon panels (LCOS) and digital micro mirror devices (DMD)), lenslet integrators are better suited to develop compact projection systems. We will show that the dimensions of the illumination system with a lenslet integrator depend largely on the used configuration of the relay lens system and the integration in the total projection system architecture.

A crucial problem with a LED-based projection system is that the optical power per unit of étendue (luminance) of a LED is significantly lower than e.g. an ultra high performance (UHP) mercury halide arc-lamp. This means that it will be difficult to get much light on the light valve(s). We can increase the acceptance étendue of the light valve(s) but this will also increase the total size of the projection system. The design of an efficient and compact illumination system with lenslet integrators is thus of fundamental importance if we want to construct a compact high-quality LED-projector which uses reflective micro-displays. The design of such an illumination system is investigated for LCOS projection systems which use time-sequential panel illumination, with the use of the Advanced Systems Analysis Program (ASAPTM).
2. LENSLET INTEGRATOR WITH RELAY OPTICS

2.1. Working principle

A lenslet integrator usually consist of two lens arrays and one or more relay lenses (see Figure 1). Each lens in the second array in conjunction with the relay lens(es) images the collected light from the corresponding rectangular lens of the first array onto the light valve. The light distribution at the light valve is thus the sum of the light distributions at all lenses in the first array. If sufficient individual lenses are used in the lens arrays, this will create a homogeneous rectangular light distribution at the position of the light valve.

The lens arrays and the relay lenses together, create the homogeneous rectangular light distribution. Their functionality however can be seen separately. The lens arrays transform the incoming light bundle with an inhomogeneous spatial and angular distribution into a light bundle with a homogeneous rectangular distribution in angle space. The spatial distribution is still inhomogeneous. The relay lens system transforms this incoming light bundle into a light bundle with an uniform rectangular spatial light distribution with an inhomogeneous angular light distribution. If the lens arrays are optimized to create an uniform rectangular light distribution in angle space and the aberrations of the relay system are minimized, then the combined performance will be good. This approach will be followed in this paper to illustrate certain phenomena. For lenslet integrators which operate at the limit of their performance, combined optimisation will give better results.

For a compact LED-based projection system we need a small illumination system, so we need small rectangular lenses (mini- or micro-lenses) for our lenslet integrator to guarantee the homogeneous illumination. An alternative approach is to use two consecutive tandem arrays of cylindrical micro-lenses. The functionality of both lens array systems however is the same: creating an uniform rectangular light distribution in angle space.

2.2. Light acceptance distribution of lens arrays

It is difficult to compare the functionality of the lens arrays with an ordinary imaging system because in this case, it are the lenses of the first array, themselves, that are imaged by the lenses of the second array. This principle and the deviations from the ideal situation can better be understood if we look at Figure 2. For a bundle of light parallel with the optical axis, the first lens collimates the light toward the centre of the second lens. The rectangular shape of the first lens will thus be imaged into angular space according to the principle of imaging with a pinhole. If the aperture of the first lens enlarges, spherical aberrations will enlarge the focused spot size and the image will be blurred. For a parallel bundle of light that makes a certain angle with the optical axis, the light is focused toward a point and the image is rotated by the second lens so that it coincides with the image from the on-axis bundle. Spherical aberrations at the second lens make that this rotation is not optimal for incident light that makes relative large angles with the optical axis. Both effects could be reduced by using lenses.
Figure 2. Illustration of light propagation in lens arrays.

Figure 3. The efficiency and uniformity in angle space of the light distribution created by lens array with paraxial optimisation.

hyperbolic lens profiles which eliminate spherical aberrations, in stead of spherical lens profiles. The problem that parallel bundles of light with a certain angle create large spot sizes and thus blurred images will not be remedied by such hyperbolic lens profiles.

We investigated the influence of the numerical aperture of the lenses and the incident light on the uniformity of the created light distribution in angle space. The configuration from Figure 2 was optimised for paraxial working conditions and the uniformity is defined as the ratio of the minimal light intensity to the maximal light intensity over the created rectangular angle distribution. We look only to the resulting light distribution in angle space that is in correspondence with the numerical aperture of the lens array and therefore the efficiency is also an important merit function. The simulations are performed for spherical lenses with a square aperture and with square incident angle distributions. The results from these simulations are shown in Figure 3.

We see that the uniformity is largest when the numerical aperture of the illumination matches the numerical aperture of the individual lenses. The efficiency on the other hand is not much reduced when the numerical aperture of the illumination increases. If the numerical aperture of the illumination is equal to that of the individual lenses, the étendue of the incoming and outgoing light distribution is equal. It is obvious that, in the case of rectangular lenses, the illumination has to have the same aspect ratio as the lenses. So our results indicate that an étendue conserving illumination of the light distribution is possible with a quite high efficiency and that such an illumination produces an uniform rectangular light distribution.

The paraxial lens configuration however is not necessary the optimal lens array configuration. For a certain radius of curvature of the lenses we adapt the distance between the lenses and the dimension of the lenses so that the numerical aperture is always equal to 0.3. We investigate again the influence of the illumination. In Figure 4 we depict the product of the efficiency and the uniformity and we see that there is an optimum when the numerical aperture of the illumination matches the numerical aperture of the lenses (black line) and that the optical performance is good.
Figure 4. The results of the simulated performance of a lens array with N.A=0.3

2.3. Relay lens configuration

The functionality of the relay lens system is to transform the rectangular light distribution in angle space, created by the lens arrays, into a rectangular spatial light distribution at the position of the light valve. This means that the light valve has to be in the focal plane of the relay lens system. We consider three different configurations for such a relay lens system. Each configuration has its own advantages and disadvantages.

2.3.1. Telecentric configuration with one lens

To give some general conclusions we follow the approach of Schreiber et al. and use the matrix method for paraxial optics and consider a thin-lens approximation for our relay lens. In reality a lens system with more lenses might be necessary to be able to reduce the geometrical aberrations, especially if the focal length is small and the étendue of the transmitted light distribution is relative large. Looking at Figure 1 and calculating the product of the different matrices we find the position and direction of the different rays.

\[
\begin{pmatrix}
  x_2 \\
  \alpha_2
\end{pmatrix} = \begin{pmatrix}
  0 & \frac{F}{F} \\
  -\frac{1}{F} & -\frac{2}{F} + 1
\end{pmatrix} \begin{pmatrix}
  x_1 \\
  \alpha_1
\end{pmatrix}
\]

We can see that, if we make the distance \( D \) equal to \( F \) we get the following equations

\[
\begin{align*}
  x_2 &= F\alpha_1 \\
  \alpha_2 &= \frac{x_1}{F}
\end{align*}
\]

Because the angular light distribution is independent of the position on the light valve we have telecentric illumination which is an advantage. The fact that a distance \( F \) is necessary on both sides of the relay lens however is a disadvantage if we want to construct a compact projection system. When designing projection architectures for reflective micro-displays we could imagine to use the free space in front and after the relay lens to place the necessary colour or polarisation splitting components. An example will indicate why this is not always possible.

Suppose that we want to develop a compact color-sequential LCOS projector with one LCOS light valve and LED’s as light sources. The projection architecture depicted in Figure 5 is a compact system. The dichroic coatings for the colour recombination are located in front of the relay lens system. Three lenses were necessary to reduce the geometrical aberrations, because the focal length of the relay lens system is very small. The polarising beam splitter (PBS) is positioned after the lens system. This projection architecture however has one important drawback. Directions of the light rays after the lens arrays correspond with positions of the light rays at the light valve. Because dichroic coatings are angle sensitive (especially in an X-cube where they are embedded between two glass interfaces) the spectrum of the light arriving at different positions will be quite different which can be seen in Figure 5 (even in the case if the colour image is transformed to grey-scale). The human eye is very
Figure 5. Projection architecture with telecentric relay lens configuration showing a non-uniform projection screen image.

Figure 6. Principle of using a telecentric projection lens to increase image uniformity.

Sensitive to such colour variations. This problem can be solved by placing the dichroic coatings after the relay lens system. However this will increase the dimensions of the total system. We can also place the lens array after the dichroic coatings but this will also increase the total dimensions of the system and well designed LED collection optics will be necessary in this case.

2.3.2. Short configuration with one lens

If we again use expression 1 and we make the distance $D$ equal to 0, we obtain the following equations for the position and direction of the different rays

$$x_2 = F \alpha_1$$

$$\alpha_2 = \frac{x_1}{F} - \alpha_1 \left( \frac{D}{F} - 1 \right)$$

It is obvious that this is the shortest configuration possible with a lens with a focal distance equal to $F$. However the illumination is not telecentric and the angular light distributions at the border of the light valve make the largest angles with the optical axis. If we place angle dependent components between the lens array and the light valve, uniformity problems similar (although smaller) to those described in the section above, will again occur. A second problem is that the reflective light valves themselves are often also angle dependent which will lead to different contrast and brightness levels with different positions on the screen.

A solution for both problems could be to use a telecentric projection lens that confines the angular light transmission so that the same cone of light, for each position on the light valve contributes to the light on the projection screen. This will reduce the optical efficiency of the projection system. If we assume a relative uniform
Figure 7. The optical efficiency of working with a telecentric projection lens to increase the image uniformity.

illumination of the lens array we can calculate the optical efficiency for this approach. We compare the étendue of the lens array output that is necessary to illuminate every point of the light valve with a light cone with half width angle $\alpha$ and the étendue of the light valve that transmits such light cones. In two dimensions the illumination étendue can be calculated with Hottel's formula:

$$E_{2D,ill} = 2 \times (AC - AB)$$

$$= 2 \times \left( \sqrt{F^2 + (2x_B + F\tan\alpha)^2} - \sqrt{F^2 + F^2\tan^2\alpha} \right)$$

This étendue value can be compared with the étendue value of the light that will be transmitted by the light valve and the telecentric projection lens

$$E_{2D,\text{value}} = 4x_B\sin\alpha$$

It is not difficult to extend these calculations toward the realistic 3-dimensional case and these results are shown in Figure 7 for different values of $F$ and $\alpha$, for a 0.7” LCOS panel. The optical efficiency is calculated as the ratio of the light valve étendue and the illumination étendue. Although this approach gives better efficiencies for large $F$ and $\alpha$ it is clear that this approach is not useful for compact LED-based projection systems. We can reduce the uniformity requirements for the points on the border of the light valve which will reduce the necessary dimensions of the lens array and increase the optical efficiency. A trade-off between uniformity and efficiency should then be sought. We note that this approach necessitates a relative uniform illumination of the lens array if we want that the brightness uniformity on the screen is high.

2.3.3. Telecentric illumination with a lens tandem

By adapting the previous configuration with an extra lens with focal distance $F$ just in front of the light valve we get the same equations (2) and (3) for the position and direction of the light rays, as in the case of a telecentric illumination with one lens in the centre between the lens array and the light valve. We get thus a telecentric illumination of the light valve with a configuration that is much smaller than the one with only one lens. This configuration solves the problem that the micro-display might have angle dependent modulation characteristics but also here we will have uniformity problems if we place angle dependent components between the two relay lenses.

3. LIGHT COLLECTORS IN COMBINATION WITH LENS ARRAY INTEGRATORS

The compound parabolic concentrator (CPC) is a concentrator that approaches the maximum theoretical concentration ratio and it can be used for the collection of LED light. If we use it for the collection of the light of LED’s with a square die, the performance will be less because the circular entrance aperture of the classic CPC is not completely filled by the square die. Optimisation of the shape can improve the performance but such techniques have not been used for this paper.

In section 2.2 we showed the benefits (optimal étendue efficiency, good uniformity, good optical efficiency) of illuminating the lens arrays with a light distribution that matches the angular acceptance distribution of the
lens arrays, which has a rectangular shape. If we illuminate the lens arrays with a light distribution with an angular distribution that is smaller than the acceptance distribution of the lens arrays, we do not optimally use the acceptance étendue of the light valve, which will reduce the possible light output. If we illuminate the lens arrays with a light distribution with an angular distribution that is larger than the acceptance distribution of the lens arrays, light will be lost which will reduce the optical efficiency. So if we calculate the étendue performance of light concentrators to be used in combination with a lens integrator it is logical to take a rectangular shape in angular space into account, in stead of working with circular angle distributions.

We simulated this étendue performance for three different concentrators. Firstly, a normal CPC with a circular exit aperture that collects the light of a LED with a square diode (see Figure 8). The étendue of the light source is equal to 13.85 mm²sr. Secondly, an analogous CPC that collects the light of a LED with a die that has the same aspect ratio as the light valve, but the same étendue value as the first LED. Thirdly, a CPC that has an elliptical exit aperture that collects the light of a LED with a square die (see Figure 8).

The second and third configuration generate light distributions with an asymmetrical angular light distribution that is better matched to the angular acceptance distribution of the lens arrays. In Figure 9 we see the étendue performance of these LED collectors for use in combination with lenslet integrators. The étendue varies with the rectangular distribution in angle space. We see that using a LED die with a corresponding aspect ratio has no advantages when used with a normal CPC. For collection optics that approach the maximum theoretical concentration ratio, such a die shape will have advantages when used in combination with a lenslet integrator.

The CPC with the elliptical aperture has the best étendue performance. However, an elliptical exit aperture is often a disadvantage, especially since the long axis of the elliptical exit aperture must be orthogonal with the long axis of the light valve. But such a shape can have advantages for certain configurations. For example with a telecentric configuration with one lens, such a shape will induce an elliptical angular distribution after the relay lens that can be used to reduce the losses due to the angular dependent colour and polarisation splitting components. A detailed analysis of such an optical architecture however, is beyond the scope of this paper.
4. SINGLE-PANEL LCOS PROJECTION ARCHITECTURE USING LENSLET INTEGRATORS

The purpose of this paper was to investigate lenslet integrators to create compact and efficient projection displays with a high image-quality. Recently, LCOS panels with fast enough switching times for time-sequential single-panel LCOS projection architectures came on the market.\(^{15}\) Such a micro-display can be used to create ultra-compact LED-based projection architectures.

The projection architecture shown in Figure 10 is implemented in ASAP and the performance of the illumination system (optical efficiency, brightness and colour uniformity) is investigated. A telecentric configuration with a lens tandem was used and the X-cube with the dichroic coatings and the PBS was placed between the lenses. We saw in section 2.2 that the lens arrays have a good optical performance for relative large numerical apertures. The small focal distance of the relay lenses however introduced significant geometrical aberrations. The lens arrays and the relay optics were optimised independent of each other. The étendue of the LED light source is again equal to 13.85 mm\(^2\).sr and the acceptance étendue of the 0.7\(^\circ\) LCOS light valve and the projection lens, equal to 21 mm\(^2\).sr. When no Fresnel losses, reflection or absorption losses are taken into account, the simulated optical efficiency of the illumination system is 86\% and the obtained uniformity (minimal to maximal intensity) is equal to 82\%.

The coatings for this optical architecture were specifically designed with the Essential Macleod\(^{TM}\)\(^{16}\) optical thin film design program to reduce the angle sensitivity, which causes non-uniform colours on the screen. The emitted spectra of the used LED’s were based on the specifications.\(^{17}\) We simulated the colour variation across the projection screen for different colours and the \(\Delta u'v'\) colour difference is always less than 0.02 which is sufficient for certain applications, since the colour variation is gradually from the top to the bottom of the projection screen. In Figure 11 we see the colour variation on the screen for cyan in the CIE\((u',v')\) color space. ASAP allows the visualisation of colour variation but we see that certain colours of our virtual LED-projector fall out of the colour gamut of a normal display. This makes it impossible to get a feeling of the qualitative colour variation that will be visible on the screen.

Certain important remarks have to be made concerning this optical architecture. First of all, it is clear that the CPC’s are responsible for the relative large dimensions of this system. Compact collection lenses with a good étendue performance are thus necessary if we want to create really ultra-compact projection systems. The specially designed colour and polarisation splitting components will increase the cost of the system which is certainly an important factor for certain applications of such ultra-compact projection systems. Furthermore, it is known that the spectral emissions of LED’s depend on the temperature and that different LED’s can have different emission spectra. It is obvious that the colour uniformity can change if the emission spectra of the LED’s will change. A detailed tolerance study based on experimental measurements of the used LED’s is necessary if we want to know the performance under all conditions.

5. CONCLUSIONS

We showed that a good optical efficiency and uniformity can be obtained with lenslet integrators with an illumination that matches the angular acceptance distribution of the lens arrays. Different configurations for the
relay optics were critically discussed and we indicated that for usage with reflective micro-displays, uniformity issues are important aspects when trying to design compact optical projection architectures. Several collection components were investigated taking the combination with lenslet integrators into account. We investigated the optical performance of an illumination system for an ultra-compact single-panel LCOS system.

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