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Peer-Phillip Ley, Marcel Philipp Held, Roland Lachmayer, "Analysis of LED arrangement in an array with respect to lens geometry," Proc. SPIE 10554, Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XXII, 1055405 (14 February 2018); doi: 10.1117/12.2290253

Event: SPIE OPTO, 2018, San Francisco, California, United States

Analysis of LED arrangement in an array with respect to lens geometry

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ABSTRACT

Highly adaptive light sources such as LED arrays have been surpassing conventional light sources (halogen, xenon) for automotive applications. Individual LED arrangements within the array, high durability and low energy consumption of the LEDs are some of the reasons. With the introduction of Audi's Matrix beam system, efforts to increase the quantity of pixels were already underway and the stage was practically set for pixel light systems. Current efforts are focused towards the exploration of an optimal LED array density and the use of spatial light modulators.

In both cases, one question remains – What arrangement of LEDs is the most suitable in terms of light output efficiency for a given lens geometry? The radiation characteristics of an LED usually shows a Lambertian pattern. Following from the definition of luminous efficacy, this characteristic property of LEDs has a decisive impact on the lens geometry in a given array. Due to the proportional correlation between the lens diameter and the distance of LEDs emission surface to the lens surface. Assuming a constant viewing angle an increase of the distance leads to an increase of the lens diameter

In this paper, two different approaches for an optimized LED array with regards to the LED arrangement will be presented. The introduced designs result from one imaging and one non-imaging optical system, which will be investigated. The paper is concluded with a comparative analysis of the LED array design as a function of the LED pitch and the luminous efficacy.

Keywords: Lens Design, Non-Imaging Optical Systems, Light Emitting Diode, LED Array, Lens Geometry, Imaging Optical Systems, Étendue, Luminous Efficacy

1. INTRODUCTION

In 1999 the first Bi-Xenon headlamp was introduced for a superior illumination of the road. Seven years later different dynamic light distributions such as town light, country road light and motorway light as well as glare free high beam additionally enhanced road safety due to the launch of Adaptive Frontlighting Systems (AFS). The next major development was Audi's Matrix beam system, first presented in the Audi A8.

Similar to the evolution of light functions to increase the safety for all traffic participants the demand for unique headlamp designs and low power consumption evolved. With regards to power consumption HID-based headlights were the first step to increase the efficacy. Xenon bulbs save up to 36% and offer a higher color temperature compared to conventional halogen bulbs. The ongoing development of the LED technology has enabled the use in automotive exterior lighting. Current LED headlights are even brighter than xenon headlights and the color temperature is closer to daylight compared to halogen or xenon headlights (see tab. 1). The excellent efficacy enables power savings up to 71% compared to halogen and 55% with respect to xenon. Additionally LEDs also have a very high durability and provide high illumination. Therefore it is not surprising that LEDs have been surpassing conventional light sources over the last few years.[1]

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Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XXII, edited by Jong Kyu Kim, Michael R. Krames, Martin Strassburg, Li-Wei Tu, Proc. of SPIE Vol. 10554, 1055405 · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2290253

Table 1. Comparsion of different illuminants.

	Halogen[2]	**Xenon HID**[2]	**LED**[*]
Luminance efficacy in $\frac{\text{lm}}{\text{W}}$	27	90	145
Power consumption in W	55	35	15.5
Estimated color temperature in K	3200	4000	6500

To maintain the high efficiency of LEDs the applied optical systems play a decisive role. But the wide variety of different LEDs in terms of radiation characteristics and size exacerbate the design of an efficient optical system compared to the standardized halogen and xenon bulbs.

2. LEDs FOR AUTOMOTIVE APPLICATIONS

In 2008 Cadillac introduced the first full-LED headlight in the premium model of the Escalade. At that time a white LED with a 1 mm^2 chip offered 175 $\frac{\text{lm}}{\text{A}}$. However todays LEDs provide around 300 $\frac{\text{lm}}{\text{A}}$.[3] Currently there are three different categories of LEDs. With regards to the power consumption a distinction is made between low- ($<$ 0.1 W), middle- (0.5 - 1.0 W) and high power ($>$ 1 W) LEDs.[4] The ongoing development leads to a next generation of white LEDs. Referred to as high current LEDs their power consumption is between 3 and 10 W. Thus, the primarily challanges in terms of the luminous intensity have been overcome.
Nowadays engineers are faced with new challenges. Especially the variety of different LED chips and packages with regards to the efficiency plays a critical role. The main focus here is on the luminous flux. Therefore a closer look at the LEDs radiation characteristics is necessary since the emission behavior of LEDs has a major impact on the lens geometry. Figure 1 illustrates different radiation characteristics of various OSRAM LEDs.

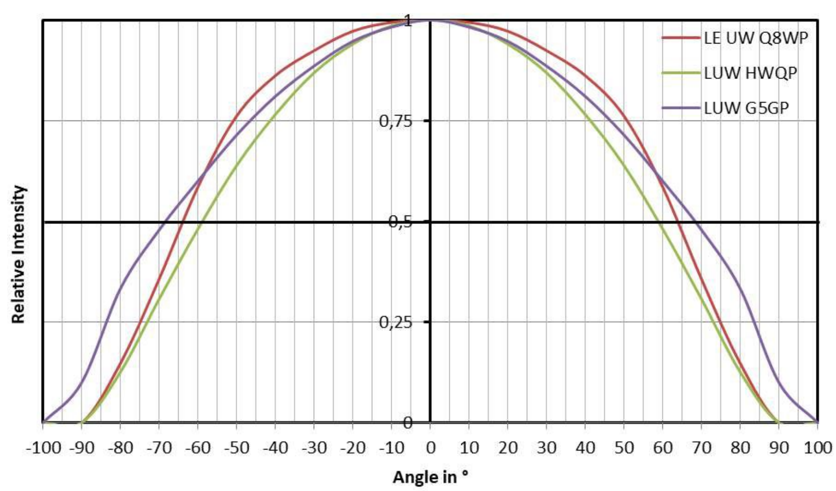

Figure 1. Comparison of the emission characteristics for different OSRAM LEDs as a function of the emission angle.

In most cases the selection of an LED for a certain application, no matter if it is in general or automotive lighting, is chosen by the Full Width at Half Maximum (FWHM) value of the luminous intensity. The FWHM indicates where the luminous intensity reaches half of the maximum value. This value depends on the emission angle of the LED. However, the distribution of the luminous intensity is not an accurate measure of the brightness. Therefore the sufficiency of choosing an LED based on a single point along the emission curve should be called

[*]OSRAM OSTAR Headlamp Pro, LE UW U1A5 01

into question. Comparing the radiation characteristic of the LUW HWQP and the LUW G5GP reveal that at narrow angles (< 30°) the LUW HWQP and the LUW G5GP show almost identical emission characteristics. At an increasing angle the deviation of the emission curves rises due to the fact that the LUW HWQP exhibits a lambertian emission pattern while the LUW G5GP shows a non-lambertian emission pattern. In addition to that the LUW G5GP emits some of the light at angles greater than 90°. This has a crucial effect on the usable luminous flux and the lens design to collect the emitted light.

3. DESIGN CONSIDERATIONS FOR LED OPTICS

The lens design depends on the purpose of the lens. Figure 2 illustrates the geometrical relation of object distance, focal length and image width using the example of a thin lens. Assuming that a collimation of the light is required the following relations are valid. For a given source with a semi diameter of S and a viewing angle of θ the distance g of the source to the lens has to be equal to the focal length f of the lens (see table 2, case 1). Assuming that the light is perfectly collimated — in reality divergence occurs — the semi diameter of the beam result in $\theta \cdot f$ and the image I moves ad infinitum. Due to the reciprocal relation of the beam radius and its divergence an improvement of the collimation leads to an increase of the beam diameter by the same factor the collimation will be improved.

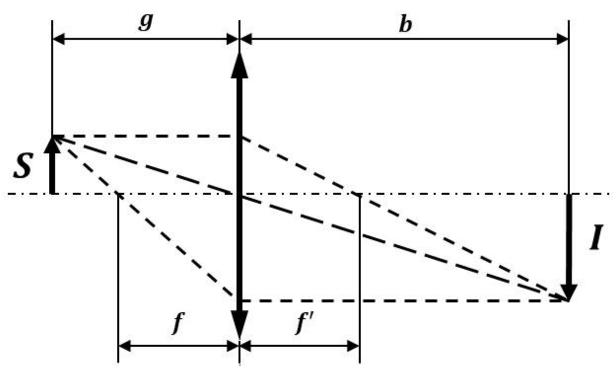

Figure 2. Geometrical relation of object distance, focal length and image width using the example of a thin lens.

For an imaging lens the position of the object S respectively the light emitting source with regards to the focal length have a crucial effect onto the image properties. If the distance g of the object S varies between infinite and two times the focal length the image I will be real, inverse and narrowed (table 2, case 2). It's position will be located between the focal length and twice the focal length. If the distance g of the object S varies between the focal length and two times the focal length the image I will be real, inverse and magnified.

Table 2. Correlation of object distance, focal length and image.

	Object S	**Image I**		
Case	**Distance g**	**Position**	**Alignment & Size**	**Type**
1	g = f	∞	-/-	-/-
2	∞ > g > 2f	f < b < 2f	inverse & narrowed	real
3	f < g < 2f	∞ > b > 2f	inverse & magnified	real

The geometrical relation of the object distance, focal length and image width illustrates the dependency among themselves. But it does not provide any information about the required lens diameter. Therefore the correlation of the Étendue and the lens design has to be considered.

4. CORRELATION OF ÉTENDUE AND LENS DESIGN

The Étendue G characterizes the spatial and angular propagation of light through an optical system.[5] It serves as a conserved quantity in an ideal optical system and is defined as

$$G = n^2 \iint \cos(\theta) dA d\Omega = \pi \cdot n^2 \cdot A \cdot sin^2(\theta) \quad (1)$$

"Simplified" the Étendue of a light source is the area of the emitting light (A) multiplied by the half viewing angle of the light (θ) respectively the area of the lens defined by the entrance pupil multiplied by the half viewing angle angle of the light (θ) for the lens. In a lossless optical system without scattering, Fresnel reflection and absorption the Étendue can be preserved. The smallest Étendue of an optical system defines the Étendue of the integral system. That implies that the Étendue enables essential statements with regards to the optical efficacy of the subsequent optical system. Knowing that a decrease of the Étendue without losses is not feasible as light propagates through the optical system, the following arithmetic expression gain in importance.

$$G_S \leq G_O \quad (2)$$

Where G_S describes the Étendue of the light source and G_O the Étendue of the subsequent optical element. To set up an Étendue preserving, thus an optical efficient lens, the entrance pupil can be designed applying geometrical optics as shown in figure 3. Here the half viewing angle of the source and the size S of the source itself imposes the required diameter of the entrance pupil. Frequently the light source is assumed as a "point source". This simplification has a crucial effect on the systems efficacy.[6]

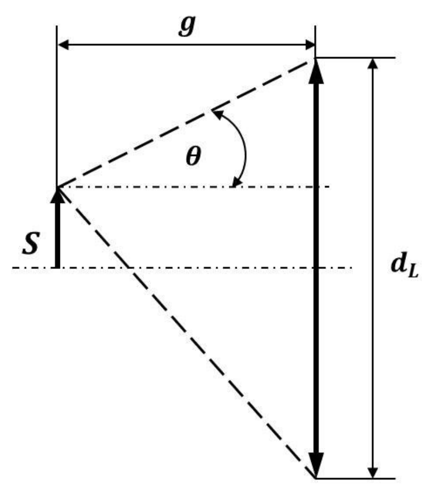

Figure 3. Geometrical correlation of the Étendue and lens design.

In addition to the half viewing angle and the size of the source the distance (g) of the emitting area to the entrance pupil of the lens determines the required entrance pupil diameter d_L. Leading to the following equation:

$$d_L = 2 \cdot (S + (g \cdot tan(\theta))) \quad (3)$$

For a compact and efficient lens design, impartial of an imaging or non-imaging optical system, the Étendue has a crucial effect onto the lens design due to the correlation of the lens diameter as a function of the emitters half viewing angle and its distance to the entrance pupil (see equation 1).

5. LENS DESIGN FOR NON-IMAGING AND IMAGING OPTICS

The ray trace of the non-imaging and imaging optics were implemented in Zemax OpticStudio 16 SP2. For the comparison of both simulations the distance of the detector to the emitting surface of the LED was set to 50.209 mm along the z axis. The pitch of the emitting surface to the first surface of the lens was set to 1 mm. For the ray trace the original rayfile package of the LUW HWQP[†]has been used. The different angular characteristics of the blue and yellow spectrum require a separation into two rayfiles. Therefore the rayfile package is parted in a blue and yellow rayfile. To receive a typical luminous flux and spectrum of the LED the following preferences were set:

- The x-, y- and z-coordinates of the yellow and blue rayfile exhibit the same position
- The luminous flux contribution for the yellow rayfile was set to 97.7% of the total luminous flux. The remaining 2.3% were distributed to the blue rayfile.
- The ray trace has been executed simultaneously with 5M rays per rayfile.

5.1 Non-Imaging Optics

Figure 5 shows the same collimating lens with two different designs and the related luminance in position space. Lens A has an ideal optical efficacy of ~82%. The lens design leads to a maximum luminance on the detector of $4.275 \cdot 10^5 \ \frac{\text{cd}}{m^2}$ in terms of the position space.

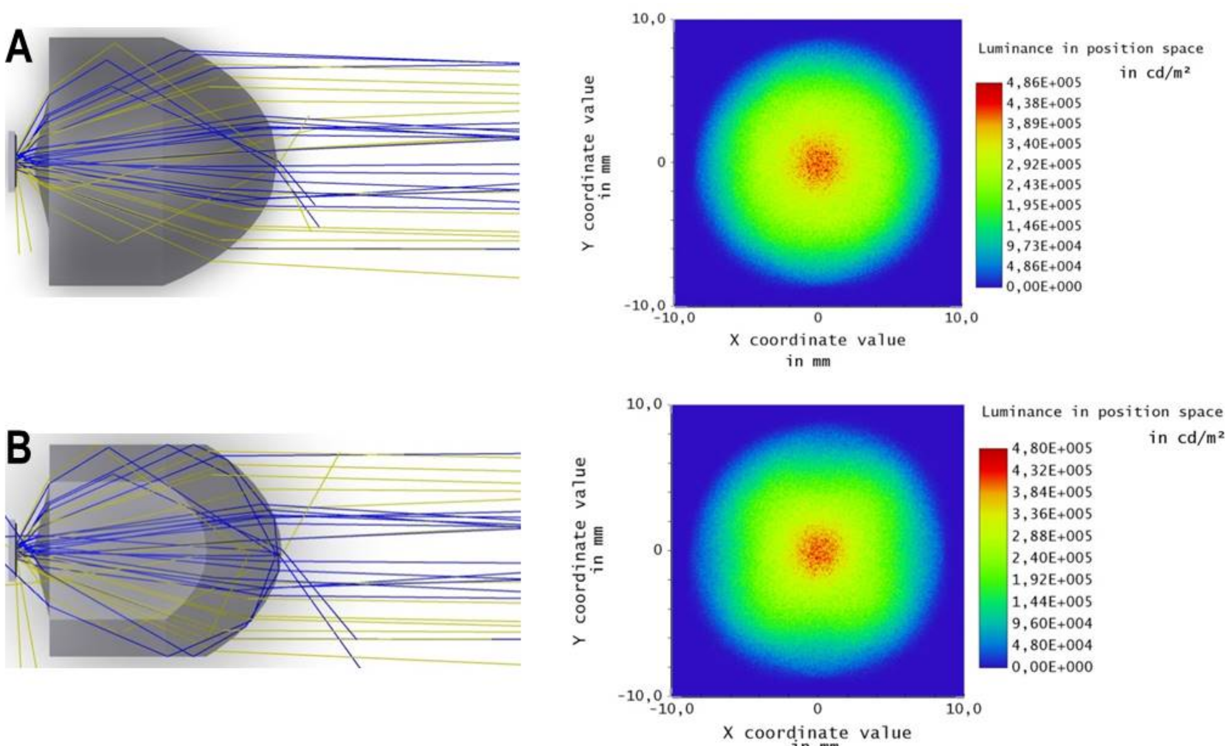

Figure 4. Comparison of the same collimating lens with two different designs and the related luminance in position space.

[†] https://www.osram-os.com/osram_os/en/applications/application-support/optical-simulation/index.jsp?fb_dir=LED%2fOSLON%2fOSLON+Black+Flat%2fOslon+Black+Flat%2fLUW_HWQP%2f (viewed on 11-30-2017)

For a more compact lens design the semi-diameter of lens A can be reduced from 7.63 mm to 6.4 mm (lens B), due to a rectangular cutting, while the lens thickness (15 mm) remains constant (see table 3). Although this modification leads to a decrease of 9% of the ideal optical efficacy it has no considerable influence onto the maximum luminance ($4.237 \cdot 10^5 \ \frac{\text{cd}}{m^2}$) and facilitates a volume reduction of 11%. That implies that the volume reduction of lens B enables a higher packing density of the LED arrangement in an array compared to lens A.

Table 3. Lens Parameters for the Collimators.

	Lens type	**Semi diameter [mm]**	**Thickness [mm]**	**Material**
Lens A	Standard	7.63	15.00	PMMA
Lens B	Standard	6.40	15.00	PMMA

Comparing the luminance in angle space of lens A and B both lens designs exhibit a good collimation of the light with a divergence of ± 13.6° (lens A) respectively ± 10.5° (lens B). However, the modified lens (B) shows a narrow distribution of the luminance reffered to the angle space compared to lens A. At ± 3.4° the luminance distribution of both lenses are identical. But with increasing angles a significant change of the luminance can be observed.

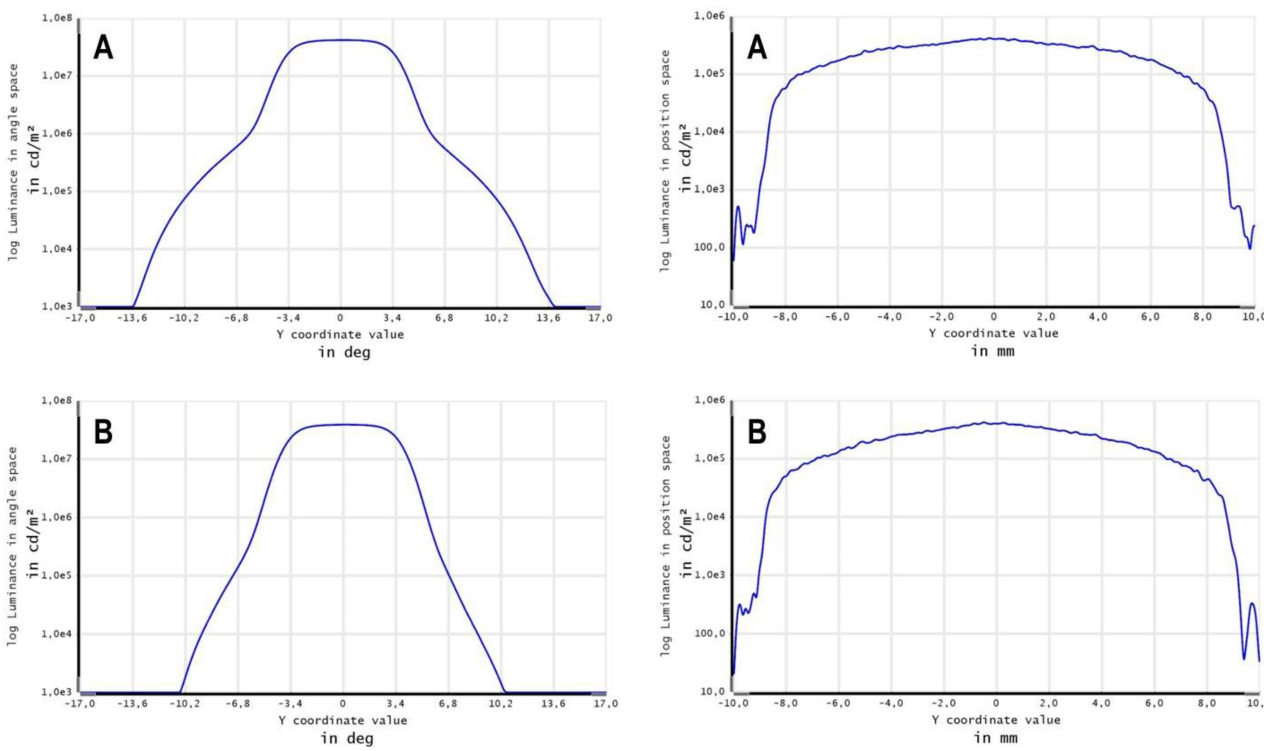

Figure 5. Comparison of the cross sections of the luminance in angle space and luminance in position space for the same collimating lens with two different designs.

At ± 6.8° the comparioson of the luminance reveals a noticeable deviation. Whereas the luminance on the detector of lens A is significantly above $1.5 \cdot 10^5 \ \frac{\text{cd}}{m^2}$ the luminance on the detector of lens B is distinctly below $1.5 \cdot 10^5 \ \frac{\text{cd}}{m^2}$. This deviation increases with further increase of the angles.

As mentioned in section 3 apart from the non-imaging optical system an imaging optical system can be applied to collect and form the light, which will be introduced below.

5.2 Imaging Optics

The optical system of the imaging optics consists of two even aspheric lenses with different semi-diameters and thicknesses (see table 4). This optical system enables an image of the LUW HWQPs emitting surface with its typical characteristic of a missing edge (see figure 6). The ideal optical efficacy of the imaging optics (~83%) is slightly better compared to lens A and approximately 11% higher compared to lens B of the non-imaging optical system. With a maximum luminance in position space of $1.385 \cdot 10^6\ \frac{\text{cd}}{m^2}$ the luminance is more than 3 times higher compared to the detected luminance of lens A and B. In addition to that the lenses are 55% (lens 1) and 31% (lens 2) smaller, in terms of the semi-diameter, compared to lens A respectively 46% and 18% to lens B.

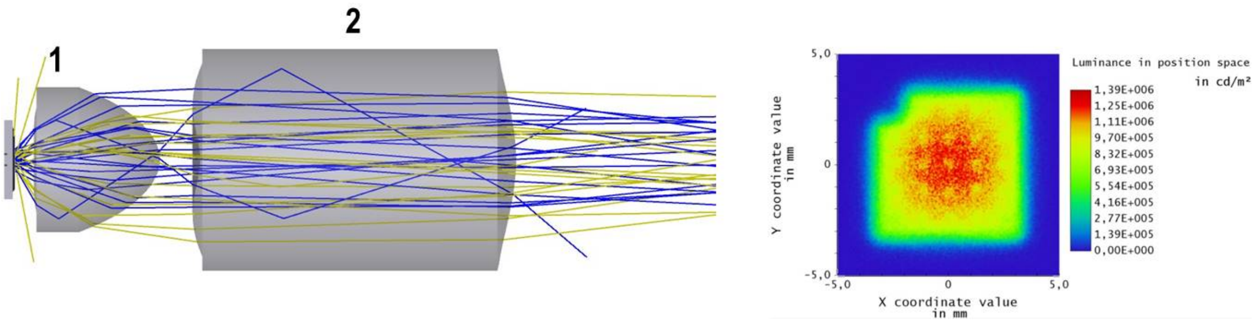

Figure 6. Imaging optical system with two even aspheric lenses and the related luminance in position space.

Due to the differing purpose of the imaging optical system — generate an image of the light source — the luminance in angle space exhibits a broader distribution with regards to the non-imaging optical system with a maximum angle of incidence of approximately ± 15.8° (see figure 7).

Table 4. Lens Parameters for the Imaging Optics.

	Lens type	**Semi diameter [mm]**	**Thickness [mm]**	**Material**
Lens 1	Even Asphere	3.44	5.99	PMMA
Lens 2	Even Asphere	5.25	15.00	PMMA

The cross section of the luminance in position space of the imaging optical system expose a more homogeneous distribution of the luminance compared to the non-imaging optical system.

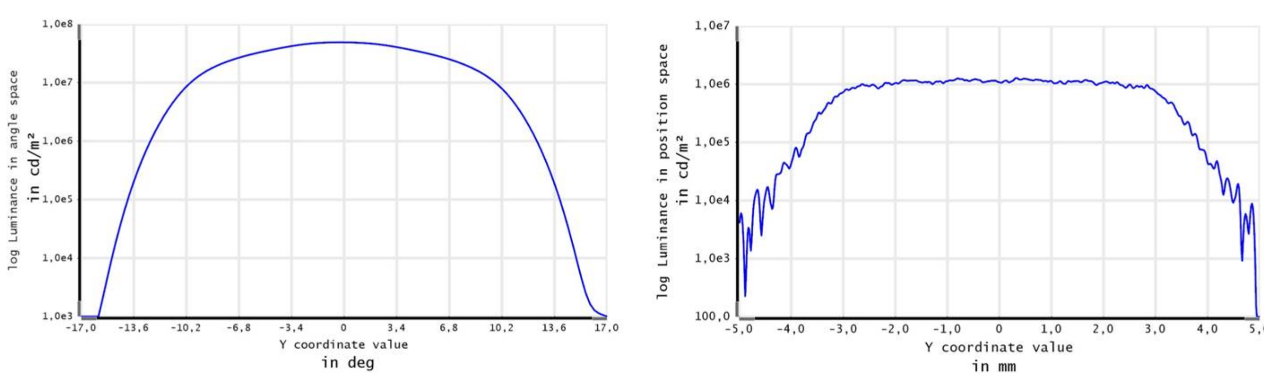

Figure 7. Cross section of the luminance in angle space and luminance in position space for the imaging optical system.

But also reveals that the acuity of the image of the emitting surface is not perfect. The reason for this is the missing steep decrease of the luminance on the detector at a certain position space. That implies for the generation of a sharp image of the emitting surface a steep decrease of the luminance in position space could have been expected at approximately $\pm$ 3.5 mm.

The comparison of the two systems illustrates that in the present case the imaging optical system conclusively holds the better optical efficacy and a more compact design with regards to the semi-diameter. The relevance of these properties in terms of the LED arrangement in an array will be discussed in the following section.

6. CONCLUSION

In this paper we excogitated the radiation characteristics of different LEDs (section 2). Furthermore we discussed two design concepts for LED optics (section 3) and its direct relation to the Étendue (section 4). We introduced an imaging and non-imaging optical system and outlined the advantages and disadvantages of both systems (section 5). Concluding the remaining question of the LED arrangement in an array with respect to the lens geometry will be discussed.

Using lens A of the non-imaging optical system and the LUW HWQP with a package size of 3.85×3.85 mm^2 the minimum pitch between each LED in an array can be 11.414 mm in each direction. That means an 3×3 LED array features the dimensions of 34.378×34.378 mm^2 with an estimated total luminous flux of about 2362 lm. Applying lens B of the non-imaging optical system the LED pitch can be reduced to 8.95 mm. As a result the dimensions of the 3×3 array can be scaled-down to 29.45×29.45 mm^2. With regards to the reduced optical efficacy of lens B (section 5.1), downscaling also means a decrease of the total luminous flux to approximately 2074 lm.

The imaging optical system consists of two lenses, where the determining distance for the LED arrangement results from the diameter of lens 2. Based on this diameter an LED pitch of 6.664 mm can be achieved. That implies a compact LED array of 24.878×24.878 mm^2 can be accomplished with an estimated total luminous flux of 2391 lm. This comparative analysis reveals that the most compact design for an LED array with high luminous efficacy is offered by the imaging optical system.

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