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Micro Pixel LEDs – Design Challenge and Implementation for High-Resolution Headlamps

Marcel Philipp Held[a], Gerolf Kloppenburg[a], and Roland Lachmayer[a]

[a]Institute of Product Development, Leibniz Universität Hannover, Welfengarten 1A, 30167 Hanover, Germany

ABSTRACT

High-resolution vehicle headlamps represent a future-oriented technology that can be used to increase traffic safety and driving comfort. Typically, selective absorbing of light using a spatial modulator like DMD, LCD or LCoS creates the light distribution of such headlamp systems. A similar effect can be generated by using LED arrays. Its additive principle generates light only in specific segments if necessary.

In general, these arrays can be distinguished between conventional LEDs arranged in an array and micro pixel LEDs. Conventional LED arrays characterize by the design (THT or SMD) with typically a few millimeters edge length. In contrast, a micro-pixel LED uses COB technology, in which individual LED dies are packed in a single housing directly next to each other at a distance of a few microns.

By increasing the array resolution, the challenges in designing an optical system for high-resolution headlamps rise. High efficiencies and contrasts call for small, accurate lens geometries and negligibly scattered light effects. Due to limited installation space and manufacturing tolerances, compromises have to be made. Ideally, the optics have to be accurate enough to image each pixel of the micro LED with high contrasts and high efficiency and still be too blurry to project the gaps between each pixel. This results in small distances between LED and optics and therefore in difficult to manufacture radii of curvature.

In this paper we specify the challenges to implement micro pixel LEDs in headlamp systems, as well as present the controllability of scattered light effects of these systems.

Keywords: Micro Pixel LED, Monolithic LED, High-resolution headlamps, Automotive Lighting, Pixel light system, Imaging optics, µAFS, AFS/ADB

1. INTRODUCTION

High-resolution headlamps can increase safety at night by segmented illumination (masking) of the traffic area. Ideally, the maximum permissible luminous flux is projected into the traffic area while traffic participants and objects are masked to avoid glare. At the same time, potential dangers can be brought to the attention of a more illuminated cone of light. Typically, the high beam function of the vehicle is divided into several individually controllable segments. The number of these segments is defined as the headlamp's resolution.

Figure 1 shows an example of an illumination scenario. In the standard high beam mode, a passerby represented by a dummy can be recognized below the traffic sign (A). At the same time, however, the traffic sign is heavily overexposed, so that no information about the type of sign can be taken. As a side effect, the driver can also be glared by back reflection. Current series headlights are therefore already able to mask individual segments in high beam mode. The sign information can thereby be clearly identified by the lower intensity (B). Due to the low resolution available so far, however, this results in the fact that the dummy is no longer recognizable below the street sign.

This results in the demand for a higher resolution and thus smaller maskable segments (pixels) in the traffic area. As a result, the road sign could be hidden approximately circular and continue to illuminate the dummy below the head (C).

Further author information: (Send correspondence to Marcel Philipp Held)
Marcel Philipp Held: E-mail: held@ipeg.uni-hannover.de, Telephone: +49 511 762 3720

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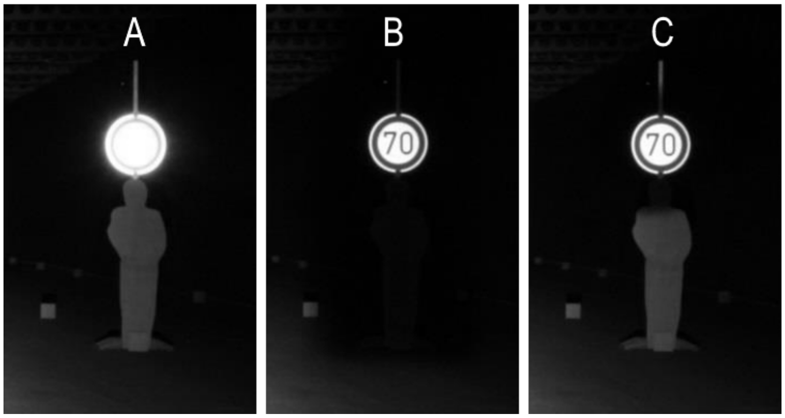

Figure 1. Maintaining the dummy visibility while avoiding glare at the same time[1]

2. HIGH-RESOLUTION TECHNOLOGIES

To implement high-resolution driving light functions, several technologies are currently being discussed.[2–6] Since every technology has its strengths and weaknesses, none has been successful in series development until now. The relevant technologies are shown in figure 2 and are described in more detail in the following section.

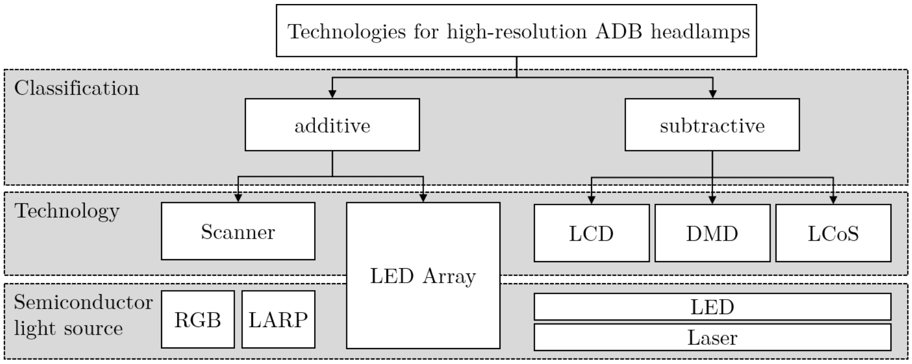

Figure 2. Overview of high-resolution technologies for adaptive driving beam (ADB) headlamps

2.1 Classification

Subtractive technologies, including Liquid Crystal Displays (LCDs), Digital Micromirror Devices (DMDs) and Liquid Crystal on Silicon Devices (LCoS), are permanently illuminated globally by a light source. By pixelwise absorption or reflection, the light image is generated. As a result, these systems typically have a low system efficiency. Furthermore, the maximum luminous flux is additionally limited by the low acceptance angle and the unsuitable aspect ratio for road traffic of the technologies. Due to the high realizable resolutions of over 100,000 pixels, these technologies are particularly suitable for detailed information projection.

Additive technologies only produce light when it is necessary. This is done by time-dependent activation of the light source. While a laser beam is deflected by a rapidly rotating mirror in scanning technologies, in LED arrays individual LEDs or LED pixels are directly imaged. This makes the LED array the only technology that is light source and modulating element in one. At present, these technologies do not yet achieve the resolution of the subtractive technologies, but can adjust the aspect ratio directly to the light distribution. Furthermore, they can achieve a significantly higher efficiency by the additive modulation principle. For this reason, the LED array technology will be explained in detail below.

2.2 LED Arrays

In principle, LED arrays can be constructed with any type of LED and consist either of a juxtaposition of individual discrete LED chips or a single monolithic LED with many individual pixels. The latter is referred to below as a micro pixel LED. Grayscale can be generated by pulse width modulation (PWM) of individual pixels.

Discrete LEDs typically have their own housing per chip. As a result, minimum distances between the LEDs, which provide an inhomogeneous light intensity, are automatically produced in an array arrangement. With at least one lens per LED, the inhomogeneities can be smoothed to produce a homogeneous light distribution. These systems thus have a high étendue. Typically, the light emission surface has an edge length between 0.5 and 2 mm and emits up to 1400 lm in the high-power version.[7] The aspect ratio of discrete LED arrays can be adapted directly to the requirements during the conceptual design phase.

Micro pixel LEDs use the COB technology, which allows multiple chips to be integrated into a single package. This is a promising alternative to discrete LED arrays, as the spacing between individual pixels is negligible. A positive side effect is the hardly noticeable inhomogeneities in the light distribution. At the same time, the étendue of the light source decreases with smaller emission area, which enables much more compact systems. An example of this is the project µAFS developed micro pixel LED Eviyos, funded by the German Ministry of Research and Education. This has a 32 x 32 blue LED array with a collective phosphor layer. Each of the square LEDs has an edge length of 115 µm with a pixel pitch of 125 µm and emits up to 3 lm.[8] Overall, the active luminous area is 4 x 4 mm$^{\mathbf{2}}$ with an aspect ratio of 1:1.

3. DESIGN CHALLENGES

In the following sections, the challenges of implementing a high-resolution vehicle headlamp with LED arrays as the light source are discussed. Since an LED array, as shown in Figure 2, is a modulating technology and light source in one, the efficiency and the image quality are determined not only by the optical system, but also by the topology of the light source and its radiation characteristics.

3.1 Emission Characteristics of LEDs

The emission characteristics of an LED can be assumed as a Lambertian emitter. Thus, light is emitted into a $2\,\pi$ half sphere. It is rarely economical to capture the complete light emission and use it for projection purposes. Typically, systems are designed to have at least 50 % of the relative light intensity (FWHM) for which the emission angle then corresponds to the acceptance angle of the first optic. For FWHM, this concludes to an efficiency of 75 %. In general, assuming a point light source, the efficiency can be easily determined by calculating the light emission in the corresponding solid angle:[9]

$$\eta = 0.5(1 - \cos 2\theta). \tag{1}$$

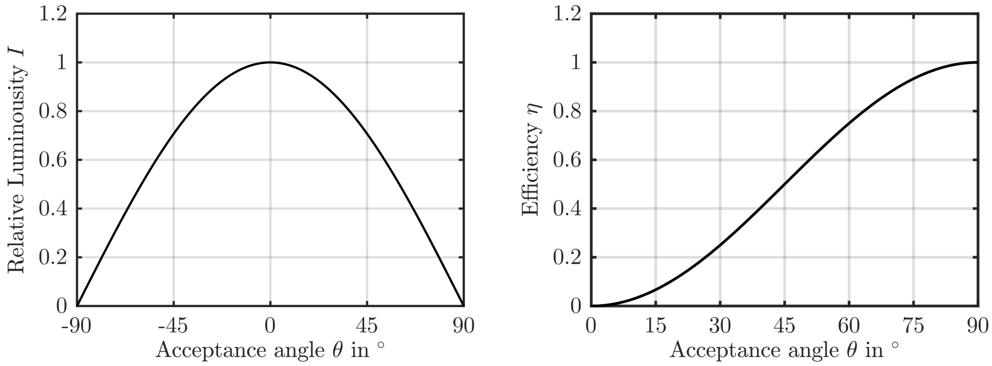

Figure 3. Emission characteristics of a Lambertian emitter as function of the acceptance angle and relative luminous intensity (left) and efficiency (right)

Figure 3 shows both the efficiency and the relative luminous intensity of a Lambert radiator over the emission angle. Angles larger than the acceptance angle of the optics are no longer deflected in a controlled manner and enter the system as scattered radiation or are lossy. When designing the optical system, it must therefore be defined at the same time how the additional radiation can either be absorbed or reused, otherwise negative effects can occur (more details are given in Section 3.3).

3.2 Imaging a light distribution

Automotive light distributions typically have an aspect ratio of at least 3:1 in order to illuminate the traffic area next to the roadway as widely as possible and thereby make signs, game pass or similar visible. Since the light distribution is generated by direct projection of individual pixels, the shape as well as the distance of the individual pixels and the aspect ratio of the array must be considered more closely.

In the direct projection of the chip emission surface, the shape of individual LEDs (or the LED pixels) together with the phosphor as well as electrical contacts are imaged, which can lead to inhomogeneities in the light distribution. In addition to the radiation characteristic, the degree of inhomogeneity is significantly defined by the distance between the LEDs. In the case of discrete LEDs, this is limited by the housing dimension, in the case of micro pixel LEDs by the contacting wires. Due to the larger dimensions of discrete LEDs, the maximum achievable resolution is inferior to the micro pixel LED systems.

In addition, the shape of the active area can create additional challenges, such as e.g. in the OSRAM BlackFlat series.[10] This LED series lacks a corner in the active area. Due to this, inhomogeneities occur despite exact juxtaposition of the pixels. From this it can be concluded that square or rectangular active areas are indispensable for the most homogeneous possible light distribution.

In order to generate a width of the light distribution of at least 3:1, there are several options available, which are shown in figure 4:

A Adapting the array aspect ratio: In the case of discrete LED arrays, it is often possible during the design process to arrange the LEDs in the desired aspect ratio on the printed circuit board.[9]

B Anamorphic projection: The aspect ratio of a pixel can be anamorphosed by projection at different magnifications. In addition, aberrations such as pillow-shaped distortion can be used to redistribute the light intensity.[11]

C Number of micro pixel LEDs: Similar to a discrete LED array, micro pixel LEDs can also be arranged in an array. As a result, the images of the monolithic LEDs in the light distribution can be arranged side by side or superimposed without having to change the aspect ratio.[12]

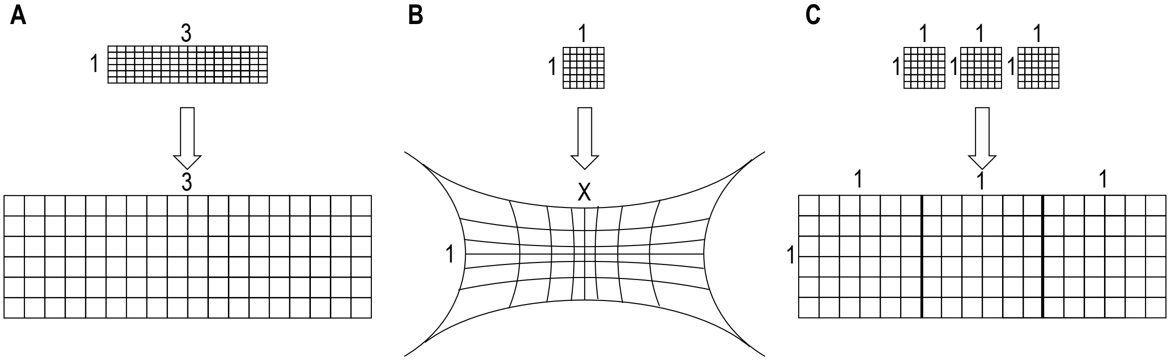

Figure 4. Optical concepts for generating an imaging light distribution utilizing LED arrays as light source

3.3 Contrast degradations caused by the phosphor layer

In masking scenarios, the maximum achievable contrast in the dimmed segments is relevant. This is mainly defined by the LED characteristics and is influenced by fresnel reflections on the optical system and the LED radiation characteristics.

The Lambertian radiation pattern already described in Section 3.1 can provide a contrast reduction between the LED chip and the phosphor. A switched on LED chip emits light in a $2\,\pi$ half space. However, since the phosphor is not applied per pixel but globally on the active LED surface, the phosphor layer of the neighboring pixel is also excited to emit light in accordance with the intensity distribution from figure 3. This can e.g. be compensated by an adaptation on the chip itself by providing separators between the pixels. Blackening the separators will reduce the efficiency of the chip, while a white separator would reflect uncontrolled light emission. With the latest micro pixel LEDs, there are no separators, so this effect is currently not compensated.

Furthermore, the contrasts in masking scenarios can be reduced by reflections on the optical system. The Fresnel reflections occur basically on any optically transparent surface and provide a discrete LED array only for slight scattered radiation in the system. By separating individual discrete LEDs through the optics, reflections can hardly stimulate the phosphor of adjacent pixels to glow. In the case of micro pixel LEDs, this is not so completely definable, because typically a single lens is used to image a monolithic LED instead of a microlens array. In Figure 5, this problem is shown schematically on the right for a micro pixel LED. Due to the lack of spatial separation of individual pixels, reflections in the optical system can cause light to excite the phosphor of the LED in places that are actually switched off by the LED itself. Reflections will no longer completely dim segments in masking scenarios. The proportion of Fresnel reflection is significantly dependent on the refractive index of the material and the angle of incidence. In Figure 5 the reflections are shown on the left as an example on a plano-convex lens with refractive index $n = 1.5$ in air. In order to be able to determine the proportion of reflections, the Fresnel formulas are used:

$$R_s = \left|\frac{\cos\theta_i - n\cos\theta_t}{\cos\theta_i + n\cos\theta_t}\right|^2, R_p = \left|\frac{\cos\theta_t - n\cos\theta_i}{\cos\theta_t + n\cos\theta_i}\right|^2 \tag{2}$$

From Figure 5 it becomes clear that for an incident angle of 60° approximately 20 % perpendicularly polarized reflection occurs. For unpolarized light, this means about a reflectance of up to 10 %. Most of these reflections typically miss the LED's phosphor and are considered uncritical. Nevertheless, there is a proportion that can ensure that in a masking scenario in the region of maximum light intensity, about 1 % of scattered radiation occurs despite the pixel being switched off. Under certain circumstances, this may already exceed the permissible legal value.

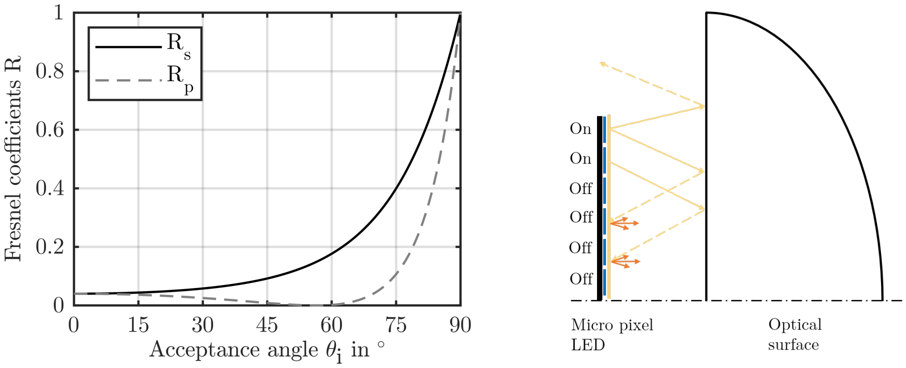

Figure 5. Fresnel reflections for $n = 1.5$ (left) and reflections caused by first lens reactivating phosphor (right)

To reduce this effect, several options are available. On the one hand, the optical surfaces can be coated with an antireflection coating and the Fresnel reflection can thus be reduced to less than 0.5 %.[13] Another possibility would be to increase the distance between the LED and the optics so that the reflections no longer hit the LED and the stimulation of the phosphor is thus prevented (see figure 5, upper pixel). The same effect can be achieved by a convex shape of the first lens surface.

4. DESIGN IMPLEMENTATION FOR LED ARRAY BASED HEADLAMPS

Figure 6 shows two typical system architectures of a high resolution LED headlamps, left for discrete LEDs and right for micro pixel LEDs. In the discrete case, the emitted light of the LEDs ① from a primary optics ②, which consists of at least 1 lens per pixel, collected and projected via a subsequent projection optics ③ in the traffic area. For micro pixel setups normally a primary optic can be dispensed with. In some cases, additional anamorphic optics ④ are necessary to adjust the aspect ratio of the light distribution. In the following sections, an LED Array headlamp with discrete LEDs will be introduced and then two prototypes with micro pixel LEDs will be discussed.

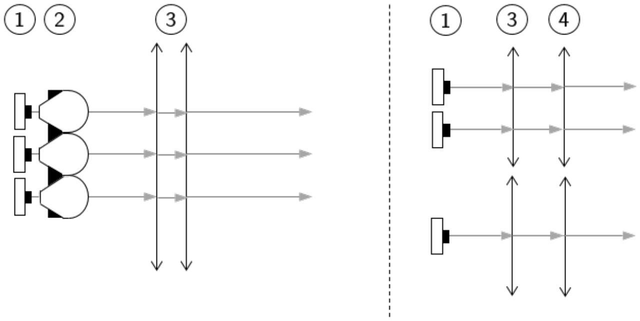

Figure 6. System architecture of high-resolution headlamps: left: discrete LEDs, right: micropixel LEDs

4.1 Discrete LED Array headlamp

The Hella Multibeam HD84 headlamp is already in serial production and has a discrete LED array of 84 pixels, divided into 3 rows. The operating principle is the same as shown in figure 6 on the left. The aspect ratio of the array is approximately 3:1. To compensate for the distance between the discrete LEDs, a special silicone optic is used, whose individual optical fibers have to be very laboriously positioned in front of each LED. Smallest positioning errors ensure a faulty display of individual pixels and an efficiency drop of 10 % per 0.1 mm mispositioning.[14] The individual optical fibers merge on the opposite optical surface to form a lens array, whereby a gap-free, diffuse emitting luminous surface is produced. In addition, an absorber is used between each lens to reduce the scattered radiation within the individual optical fibers. The diffuse illuminated area is then projected onto the street via an achromat similar to concept A.

4.2 Micro Pixel LED headlamp prototypes

Möllers et al. present a prototype projecting three Eviyos chips with four-lens optics onto the road. Two plano-convex lenses focus the light emission and two more project the square pixel to an aspect ratio of about 3:2 on the street. This corresponds to a combination of the anamorphic concept B and the combination of several micro pixel LEDs into a line array according to concept C from chapter 3.2. The projection concept is shown in figure 7.

Due to the plano-convex topology of the first two lenses, fewer Fresnel reflections hit the micro pixel LED, which increases the contrast in masking scenarios. To achieve an intensity drop to the outside, an off-axis arrangement of the third micro pixel LED is used. Overall, the headlamp has a resolution of 3072 pixels, which achieves a masking resolution of 0.34° horizontally and 0.23° vertically. Despite the high luminous flux of more than 9200 lm provided by the micro pixel LEDs, only 4200 lm are achieved on the street with a maximum illuminance in 25 m of about 100 lx. From this an efficiency of approx. 45 % can be calculated. Overall, the illumination of the left (right) headlights is -40° (-11°) and 11° (40°).[15] The resulting superimposition of both headlights achieves a maximum illuminance of up to 200 lx.

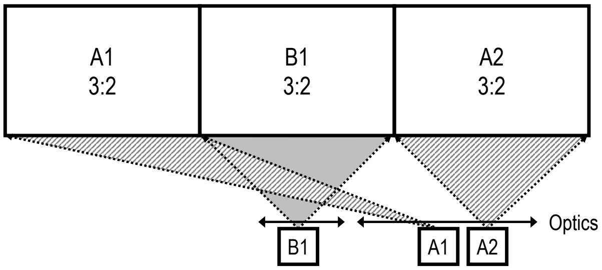

Figure 7. Side by side projection concept of anamorph pixels with aspect ratio of 3:2

Trommer et al. present a prototype with four Eviyos chips. The projection concept is shown in Figure 8. The concept projects the LEDs without changing the aspect ratio similar to concept C directly onto the road, reducing the optical system to three lenses. This reduces on the one hand the number of Fresnel reflections, while a plano-convex (biconvex) first (second) lens further reduces the retroreflections which impinges on the LED surface. At the same time, an absorber is integrated in the optics housing to further increase the contrasts. This lowers the luminous flux to 5700 lm despite the number of four light sources. It reaches a maximum illuminance in 25 m of 110 lx, which suggests an efficiency of approximately 46 %. The result is a resolution of 4096 square pixels with a masking resolution of 0.25° horizontally and vertically. Overall, the illumination of the left (right) headlights is about -28° (-5°) and 5° (28°).[12] As a result, the two headlmaps are superimposed in the range -5° (5°) and produce twice the illuminance of up to 220 lx.

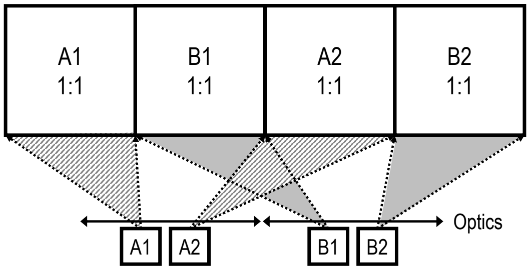

Figure 8. Side by side projection concept of pixels with aspect ratio of 1:1

4.3 Optimization potentials

Discrete LED arrays can control the occurring reflections well by the spatial separation of the pixels with a primary optics and on the other hand adjust the aspect ratio directly by the aspect ratio of the array to the light distribution. At the same time, however, the primary optics provide increased effort in the alignment of the individual optical fibers and increase the pixel size by compensating the LED distances. Therefore, the realizable resolution is several 100 pixels, which allows first masking scenarios similar to Figure 1 B.

The presented micro pixel LED prototypes have an increased resolution due to the COB technology and are superior to the discrete LED approach in precise masking. At the present time, however, the micro pixel LEDs have an aspect ratio of 1:1, which is not necessarily suitable for direct projection into the road. Therefore, the approach is there to use several micro pixel LEDs and to project these side by side in the traffic space. However, instead of arranging them side by side with minimal overlap, the individual LEDs could be deliberately superimposed, thus not only increasing the illuminance, but also reducing the number of light sources and thus the energy consumption. In the future, this could be further supported by adjusting the aspect ratio of the micro pixel LEDs to better meet the requirements of automotive light distribution. This would reduce the number of lenses in the optical system and enable more efficient beamforming.

5. SUMMARY AND CONCLUSION

In order to significantly increase safety and comfort at night, several technology concepts are currently being discussed. One of them is the LED array technology, which is already being used in series. These use discrete LEDs, which limit the resolution due to the relatively large emission area. An alternative to this are micro pixel LEDs, which have significantly smaller emission areas. When using micro pixel LEDs as a light source, some new challenges emerge, which in this paper have explicitly addressed the imaging into the traffic space and scattering reflections. Imaging a single pixel can already be challenging since the emission characteristics also activates surrounding pixels to glow. Due to fresnel reflections on optics this effect can be amplified. Since the aspect ratio of current micro pixel LEDs is square, different optical concepts can be used to form an automotive light distribution. Several research concepts for this approach have been presented and possible optimization potentials have been demonstrated.

Micro pixel LED technology has great potential to be the next evolutionary step for high-resolution headlight systems. Particularly interesting will be the further development of the maximum resolution and luminous flux per micro pixel LED. Resolutions of up to 30,000 pixels and luminous fluxes of up to 10,000 lm are quite realistic.

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