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Headlamp Innovations: Optical concepts for fully adaptive light distributions

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ABSTRACT

Glare avoidance and marking lights are two of the many functionalities offered by advanced automotive headlamps such as Matrix-LED systems. DMD-based headlamps offer resolution enhancements to these two adaptive lighting functionalities. This is achieved via a precise optical system that exhibits high marking and glare avoidance efficiencies. This work evaluates two concepts for an optical system that enables fully adaptive light distributions.

Light distributions from automotive headlamps are characterized by a wide aspect ratio and a centrally located hotspot marked by a high luminous intensity. Due to the popular use of DMDs in video projectors, DMD properties counter-productive to automotive applications are regularly encountered. For example, DMDs for projectors require to be illuminated homogeneously in order to obtain a homogeneous projection whereas headlamps require a hotspot centric distribution. It is possible to digitally create a hotspot with conventional projection optics but the results come with a significant loss in optical efficiency.

The two concepts for an optical system compared in this paper are: anamorphic optics and optics with pincushion distortion. This comparison is conducted using optical simulations. Photometric measurements are then taken from a vehicle headlamp based DMD and distorting optics and compared with the simulation as a validation step. Due to the strong distortion of the lens system the relation between the DMD image and the final light distribution is highly non-linear. The paper is concluded with key observations with regards to this non-linearity.

Keywords: Headlights, DMD, High Resolution Headlamps

1. INTRODUCTION

With the introduction of AFS headlamps (Adaptive Front-lighting Systems), beside the conventional light functions low beam and high beam, new functionalities, that provide a situation depend light distribution, are possible. For example a motorway light provides a narrow beam to extend the visibility range. A headlamp controller automatically chooses a suitable light function based on information of e.g. speed and steering angle.[1] The high beam mode provides a good visibility of the road and shoulders at night. Unfortunately, drivers rarely activate the high beam mode because of its glare potential for other road users. New driver assistance systems based on front cameras can automatically control the activation of high beam mode to increase the time this mode is used for better road visibility. A further improvement of this functionality is enabled by a new headlamp system called 'matrix beam', that was first introduced by Audi in their high class model A8.[2] Matrix beam headlamps can switch off or dim small parts of the light distribution to create a dark tunnel in order to prevent glare while using high beam mode. This is possible by implementing individually controllable LEDs (50 – 100), that altogether create a full light distribution.

A next step to improve the glare-free high beam and other functionalities is to increase the number of controllable elements. The so called *high resolution headlamp* or *pixel light* systems can address 100 000 and more individual pixels. Compared to matrix beam headlamps complete new functionalities such as on-road projection of symbols become possible. With pixel light systems adapted light distributions for a very high

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number of traffic situations and light conditions can be created using only one headlamp system. Besides the mentioned glare free high beam, the technology can be used to highlight pedestrians or animals to warn the driver. Due to the possibility of controlling the light intensity for every pixel individually, contrast of e.g. road signs can be optimized for a faster recognition and avoidance of glare.[3]

In today's cars mainly displays provide information and warnings to the driver. To see and comprehend these information it is necessary that the driver turns his eyes and adapts to a shorter distance. An improvement to this are head-up displays that project information on a virtual image plane in front of the car. A further enhancement are head-up systems that provide an augmented reality to display contact analogue information, e.g. an arrow for navigation that is virtually lying directly on the correct lane. Beside a high computational effort, this system requires a distinct information of the driver's eye position. With high-resolution headlamps it is possible to project information directly on the road to provide the driver with contact analogue data whereas the exact position of the driver's eye is not important to know. Compared to other solutions limited contrast at twilight is a drawback.

2. TECHNOLOGIES FOR HIGH-RESOLUTION HEADLAMPS

2.1 DMD

DMDs (Digital Micro-mirror Devices) are area-based light modulators consisting of many individually adressable mirror elements. By switching each mirror either to an on or off state and illuminating the DMD, a projection image is created. This way, fully adaptive light distributions can be realized, where each micro-mirror element represents a pixel in the resulting image.

In contrast to multimedia projectors where a homogenous projection image is required, vehicle light distributions require a high illuminance in the image center (hot spot). This can be achieved by pre-shaping the light and increasing the illuminance in the central part of the DMD.[4] The maximum illuminance is limited by the thermal capacity of the DMD so that further post-shaping of the light can be necessary.

For usage in an automotive environment, high requirements especially regarding temperature stability have to be met. DMDs certified for automotive applications are available in WVGA resolution.[5]

2.2 LCD

Another approach is the transmissive use of an LCD (Liquid Crystal Display) element. LCDs consist of an array of small elements that, depending on the switching state, rotate the polarization direction of the incident light or leave it unchanged. Through a polarizing filter, only light of a certain polarization direction emerges and thus generates the desired image. For this reason, it is also necessary to use polarized light in combination with an LCD.

In contrast to the DMD, the optical setup can be made significantly more space-saving, since the optical path for the reflected light is eliminated. Thus, the light source can be placed very close behind the LCD. On the other hand, the efficiency of conventional LCDs in combination with unpolarized light sources is lower than that of DMDs and it can be increased by using polarized light sources like laser diodes.[6]

2.3 LCoS

The abbreviation LCoS stands for *Liquid Crystal on Silicon* and describes a technology in which an LCD element is not used transmissively, but in a reflective setup. The advantage of such a system compared to LCDs is the possibility to mount the control electronics behind the modulation surface.

As with the LCD polarized light is directed onto a liquid crystal layer and rotated in its polarization. This is usually realized via a polarizing beam splitter.[7] Directly below the liquid crystal layer is an aluminum layer, which reflects the incident light. Since the light rays thus pass through the polarizing liquid crystals twice, the rotation of the polarization direction is 45° in each pass, in total 90°.[7]

The reflective use of the LCoS is advantageous over an LCD especially with regard to the thermal connection. Thus, the reflective layer can be connected directly to a heat sink, while the transmissive use of the liquid crystal layer does not allow this. If the light of both polarization directions can be used by directing it to a separate modulator, a large part of the original luminous flux can be used and the system efficiency can be increased considerably. However, comparable results can also be achieved through the use of two LCD elements.

2.4 LED Array

When using an LED array as a light source for a high resolution headlight, the actual light modulation is not independent of the light generation, as is the case with the other methods presented. Instead, many individual LED chips are arranged side by side in such a way that a light matrix is created in which each element can be switched. The individual semiconductor chips are controlled like conventional LEDs.[8]

This setup is especially challenging regarding an increase in the number of individually addressable elements and their size. If more LEDs are installed in an array, the number of leads for the control and energization also increases. Because of these leads, the individual LED chips can not be placed directly next to each other and the resulting gap between the light spots must be considered in the system design.[9]

3. SYSTEM SETUP

3.1 Goals and problem description

For the system to be examined, a high-resolution headlamp with a DMD module has been set up. This is advantageous because an automotive certified DMD chip is available and additionally very a high contrast can be achieved when using a DMD.[10]

DMDs are mainly used in digital projectors. Typical sizes range from 0.3" to 0.95" with an aspect ratio of 4:3 to 16:9. Target parameters of video projectors are e.g. a homogeneous illuminance distribution and a high contrast ratio. The photometric requirements of headlamps differ from those of video projectors, so that an adaptation of the optical system is necessary to use DMDs to create complete automotive light distributions.

The goal of this paper is to show that DMDs can be used in combination with special projection optics to generate complete light distributions. First of all, requirements for headlamp distributions are set up and then the optical system of a typical application with DMDs is analysed. Based on this, two concepts for projection optics are presented and compared with each other using simulations. Finally, results of the photometric measurements of the prototype are presented.

3.2 System requirements

Günther compares high beam distributions of reflector and projection headlamps in his PhD thesis. The mean value of illuminance of his measurements are shown in Figure 1.[11] The trend is towards the development of headlamps with a central hotspot over 120 lux which decreases with a high gradient. The illuminance is measured on a wall in 25 m distance.

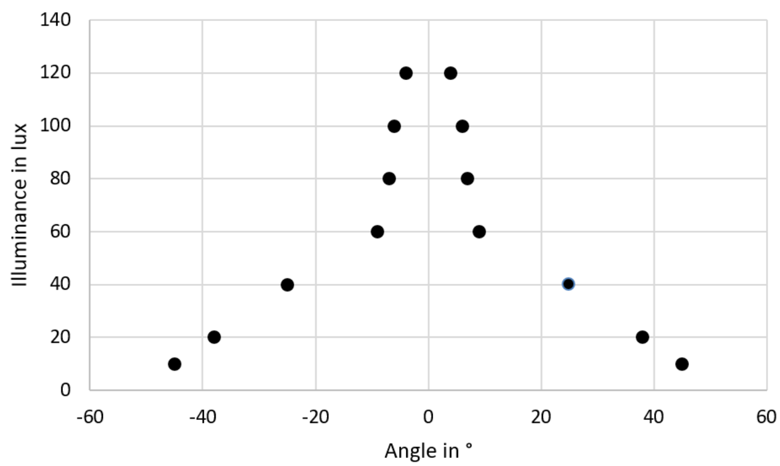

Figure 1. Mean illuminance value of horizontal cuts through state-of-the art light distributions (Reflector and Projection Systems)[11]

The shown cut through a light distribution of a current headlamp is the result of a continuous improvement with regard to a good illumination of the traffic area with two light functions: low beam and high beam. With the introduction of adaptive lighting functions (AFS, Adaptive Frontlighting System) and new Matrix-LED headlamps, new degrees of freedom are created for the design of lighting functions. Due to the variety of design possibilities with high-resolution headlamps, future light distributions will look different from those previously described.

The analysis of today's headlamps will be used to derive the following requirements for the system to be developed. These requirements later form the basis for comparing different concepts that can be used to realize a high-resolution headlamp with DMD.

Requirements for automotive light distributions:

- Minimum horizontal opening angle of ±25°
- Minimum vertical opening angle of ±8°
- Illuminance in hotspot 120 lx

These requirements result in two challenges, which need to be solved when developing a high-resolution headlamp with DMD:

- Adjustment of the aspect ratio (From DMD: 4:3 to light distribution: 4:1)
- Generation of a central hotspot

4. OPTICAL CONCEPTS

The two challenges mentioned above can be solved by projecting the image of the DMD to the traffic space using conventional projection optics with a large magnification. The consequence would be that a very large output luminous flux is needed to reach at least 120 lux in the center of the light distribution. Many mirrors at the sides of the DMD would permanently direct light into the absorber, resulting in extremely low system efficiency.

To overcome these challenges it is advisable to design the optical path as well as possible and then make only small adjustments by dimming individual pixels of the DMD. Therefore, the following section first explains the optical path of a DMD application and then analyses how to design the components for a high-resolution headlight.

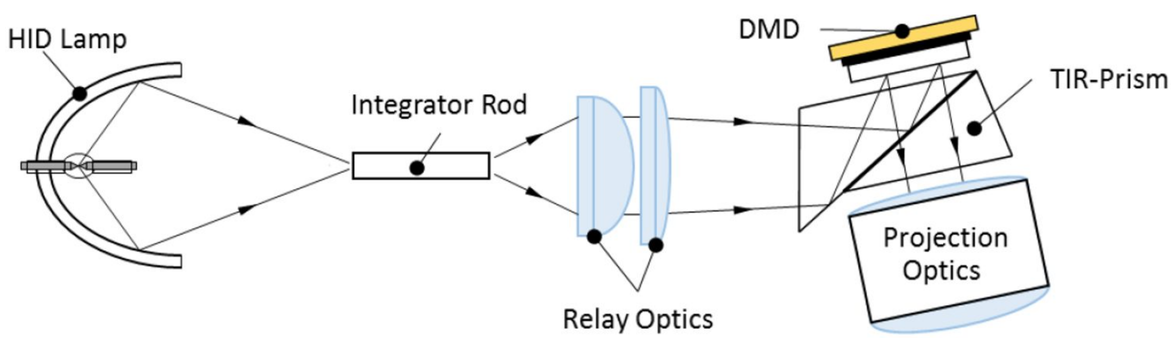

Figure 2. Typical DMD imaging system[12]

Figure 2 shows the setup of a video projector with a DMD. The color wheel needed for color generation is not shown because it is not needed for a monochromatic headlight. The light source, which can be depending on the application a gas discharge lamp, LED, LED array, or laser-based light source, is imaged to the DMD by a relay optics. In order to separate the path of incident and reflected beams, a TIR prism is used in this example. In addition to this telecentric setup, a non-telecentric setup without a prism but with e.g. a free-form mirror is possible. The relay optics is designed so that a homogeneous image of the light source is created on the DMD. The light source in this case is the output aperture of the homogenizer. The DMD is imaged by the projection optics on a screen and creates a homogeneous and high-contrast image. To use a DMD for complete light distributions, the aspect ratio of 4:3 (standard automotive DMD format) must be adjusted to approx. 4:1. Since the projection optics is the only optical element behind the DMD, only with this the adjustment of the aspect ratio can be done. The necessary central hotspot can be generated in several ways. It is possible to design a light source, e.g. an LED array, to that this light source already generates the hotspot. The relay optics can be used to illuminate the DMD inhomogeneously with a high illuminance in the center. In this approach, the thermal aging of the DMD must be considered, which strongly depends on the temperature on the array. The projection optics can also be designed in such a way that with homogeneous illumination of the DMD a hotspot is created in the center of the light distribution.

Since both challenges can be solved with the projection optics, it is also the focus in this paper. If a higher system complexity is allowed, the possibilities mentioned before can be combined to optimize the result. Two concepts for projection optics are presented below, analyzed and compared using optical simulations. To compare the concepts directly, the following target parameters are used for both concepts:

- Size of the DMD: 0,7", 4:3
- Minimum of 120 lx in central hotspot
- Minimum horizontal opening angle of ±25°, (1 lx in 25 m)
- Minimum vertical opening angle of ±8°, (1 lx in 25 m)

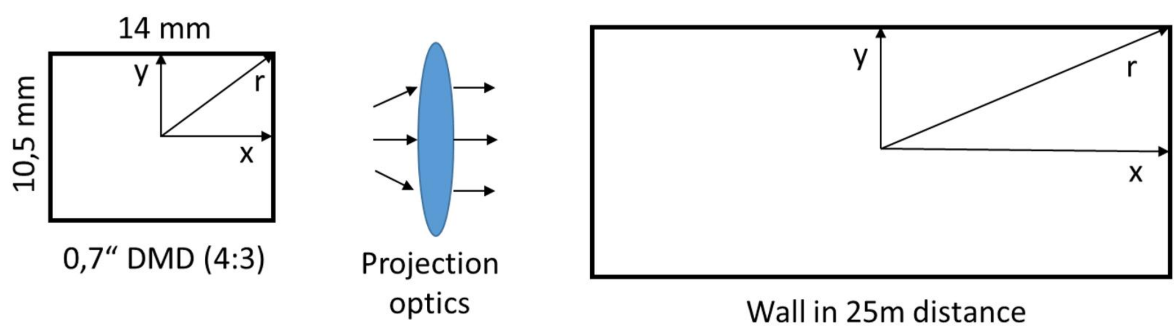

Figure 3. Simulation setup to compare concepts of projection optics

4.1 Concept 1: Anamorphic projection optics

In contrast to spherical or aspheric lenses, cylindrical lenses offer the possibility to independently focus or expand incident light in two directions. An optical system with this property is called anamorphic. In the application considered here, with an anamorphic projection optics it is possible to increase the aspect ratio of the image of the DMD and at the same time redistribute light from the sides to the center of the light distribution.

The goal of Günthers research is the development of a DMD headlamp for complete light distributions.[11] As a projection optics he uses a system of three lenses, whereby two of those are cylindrical lenses. In order to understand the potential of this idea for the DMD headlamp, the projection optics developed by Günther is modelled and analysed in Zemax Optical Studio.

The two anamorphic elements make it possible to set up a different magnification for the x and y directions. Using the built-up simulation model, it is analysed where certain points on the DMD impinge on the wall in 25 m distance. In the x-direction, points from 0 to 7 mm from the center of the DMD are considered, and in the y-direction points from 0 to 5.25 mm (Figure 3). The corresponding angular positions of the considered points can be derived from the simulation of the projection optics (Angular position, Figure 4). From this data, the magnification can then be calculated, which is shown in both cases as a gray line. In the horizontal direction, the magnification increases towards the edge of the DMD (Figure 4, left) and the light is redistributed from the edges to the center. In the vertical direction, the magnification is almost constant, which results in a homogeneous distribution of light in this direction.

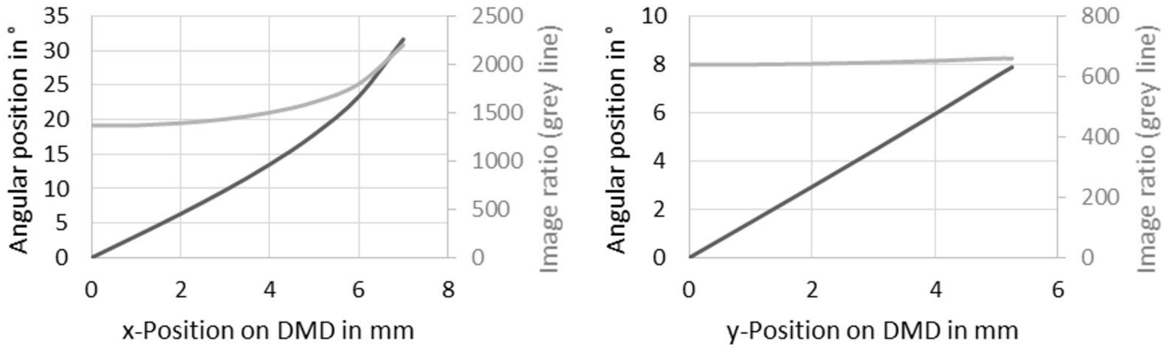

Figure 4. Angular distribution and image ratios of the anamorphotic projection optics. Left: horizontal. Right: vertical.

With this optics, the aspect ratio of the image of the DMD can be freely adjusted. The created simulation model for concept 1 results in a horizontal opening angle of ±32° and a vertical opening angle of ±8°. The distribution thus has an aspect ratio of 4:1.

4.2 Concept 2: Radial distortion optics

The second concept takes advantage of the characteristic of the pincushion distortion. This effect occurs when apertures confine the beam in front of or behind a major plane of the optical system. A strong pincushion distortion results in two usable effects (Figure 5).

- Pixels in the center of the image are imaged smaller than pixels on the sides. This leads to a redistribution of the light from the edges to the center of the light distribution, creating a central hotspot.
- The pincushion distortion of a rectangle changes the aspect ratio of this rectangle (red in Figure 5).

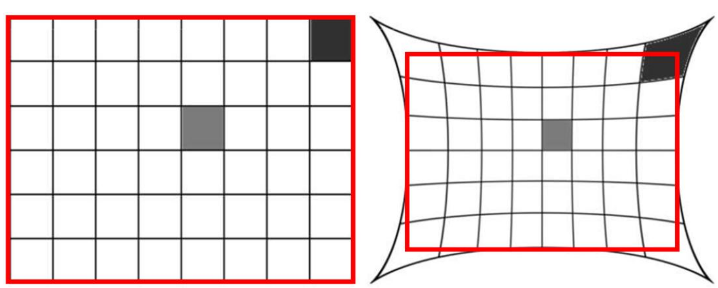

Figure 5. Principle of the pincushion distortion

The distortion and the change in magnification in this concept depend only on the radius of the optical system. In order to be able to compare the system better with concept 1, only the horizontal part of the distortion is shown in Figure 6 on the left. At the side of the 0.7" DMD an angle of approx. 22° is reached. The curve for the vertical distortion is identical, but reaches only 5.25 mm on the x-axis, which corresponds to an angle on the measuring wall of 10°. The aspect ratio is 2.2:1. The aspect ratio and the redistribution of the light to the center can not be set independently in this concept. It should also be noted that the size of the DMD has been chosen so that both concepts can be compared. For the simulation of the second concept and the development of the prototype a 0.67" DMD with 16:10 aspect ratio was used. The resulting aspect ratio on the screen is shown together with the simulation results in the next section.

On the right in Figure 6 the direct comparison between the two concepts is depicted. The greater curvature in the graph of the second concept indicates a greater redistribution of light from the sides to the center. Using the same DMD size of 0.7", the first concept achieves an almost 10° wider light distribution.

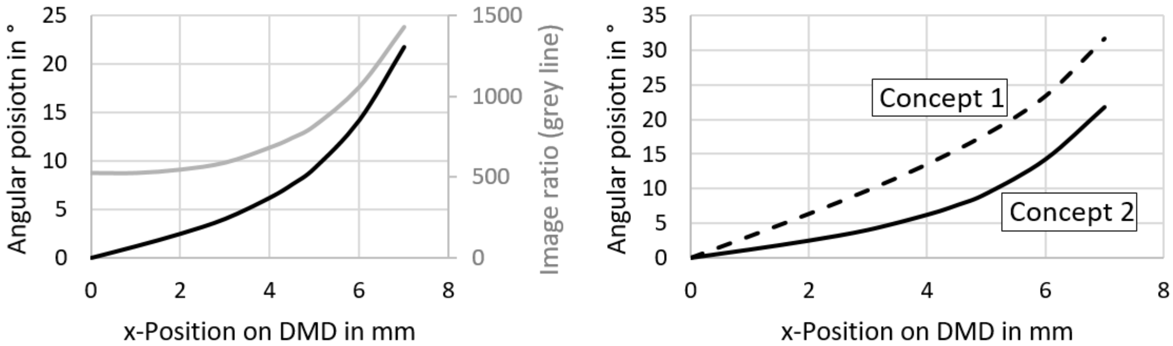

Figure 6. Left: Angular distribution and image ratio of the distortion projection optics. Right: Comparison between concept 1 (dashed line) and concept 2 (solid line).

4.3 Simulation Results

The following figure shows the simulation results of the two concepts. In both simulations, the input luminous flux into the system was adjusted to achieve a similar illuminance in the hotspot of the light distributions of about 125 lx. In the first concept 18 000 lm are necessary for this, in the second approx. 5 200 lm.

This big difference can be seen in the sectional views in Figure 7. As already shown in the comparison of the concepts, concept 2 shows a distinct redistribution of light both from left and right, but also from above and below. This leads to a very narrow light distribution in the horizontal cross section. The first concept achieves a significantly wider illumination up to approx. ±35°. Unlike in the second concept, in the simulation of the first one no distinct hotspot is visible. This leads to a three times higher input luminous flux to achieve the required illuminance.

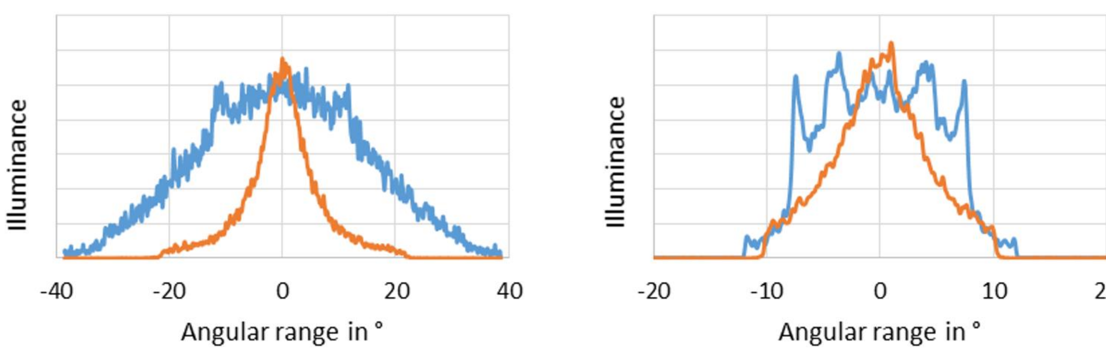

Figure 7. Left: Horizontal cross section. Right: Vertical cross section. For concept 1 (blue) and concept 2 (orange).

5. PROTOTYPE SETUP AND VALIDATION

In order to investigate the properties of high-resolution headlamps and to develop new lighting functions, a headlamp based on a video projector was set up at IPeG. The commercially available video projector Optoma EH505 uses a 0.67" DMD and has a WUXGA resolution of 1920x1200 pixels. With conventional projection optics, the video projector achieves an opening angle of ±32° horizontally and ±20° vertically with a homogeneous illuminance of approx. 7.5 lux at a distance of 25 m. In total a luminous flux of approx. 4 300 lumen is available. In order to generate complete light distributions with this projector, the projection optics have been replaced by the concept 2 optics. Figure 8 shows the result of the photometric measurement of the system. The maximum angle of the light distribution refers to a position where an illuminance of 1 lux is exceeded. This results in a usable width of the light distribution of ±26° and a height of ±11°. The total luminous flux is 4 150 lumen and the illuminance in the hotspot is 140 lux. Therefore the prototype fulfills the requirements.

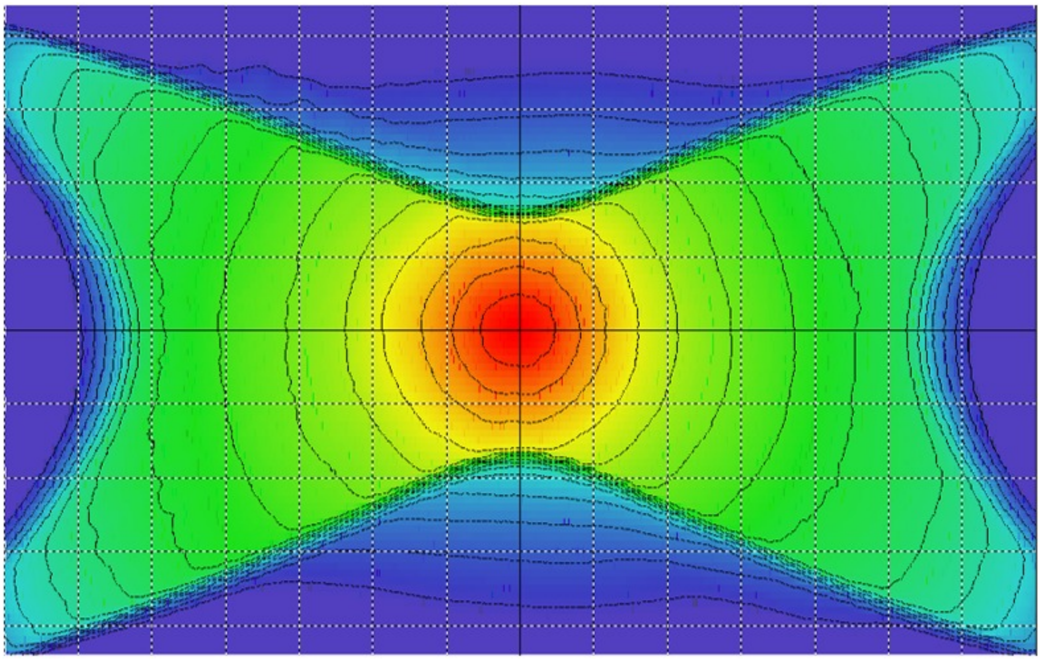

Figure 8. Light intensity distribution of prototype.

With the built-up high-resolution headlamp complete light distributions can be generated. The design of the light functions is completely free, e.g. to project information of a street sign in the low beam distribution (Figure 9).

6. CONCLUSIONS AND OUTLOOK

This paper compares two optical concepts to use a DMD in headlamps to create complete light distributions. One using anamorphic projection optics and the other using optics with pincushion distortion. With both concepts, the aspect ratio can be adapted according to the requirements. In order to achieve the required illuminance in the hotspot, the first concept requires such a high input luminous flux that no étendue matched light source is available. In the form presented here, Concept 1 is not suitable for generating complete light distributions, because the redistribution of light to the center is not sufficient. Therefore the second concept is pursued further for the development of a prototype. After that, measurement results and a possible function are shown. The preforming of light before the DMD together with the first concept also has the potential to meet the requirements. Another option is to supplement the radially distorting projection optics from concept 2 by a cylindrical lens. Not considered in this contribution, but already covered by other researchers, is the possibility to use the DMD only for a part of the light distribution, in order to integrate a high-resolution adaptivity into a light distribution. In future work, these issues will have to be further investigated in order to find a solution with low complexity and high efficiency for the development of high-resolution headlamps.

Figure 9. Traffic sign information on top of a low beam distribution[13]

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