

Review Article

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High-resolution headlamps – technology analysis and system design

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Abstract: High-resolution vehicle headlamps are the technological way to intelligently illuminate the traffic area to increase safety and comfort. For the technical realization of these headlamps, different technologies come into question, which are the subject of intensive research at universities and among the manufacturers. We present an overview of the possible technologies and analyze their potential for use in high-resolution headlamps. Furthermore, we explain how the design of the optical system for the different technologies can be made. Another part of this paper is the comparison of published prototypes of high-resolution headlamps and the compilation of key properties.

Keywords: AFS; automotive lighting; DMD; high-resolution headlamps; LCD; LCoS.

1 Introduction

In the automotive industry, conventional headlamps consisting of a light source and a reflector or a lens are being replaced more and more by systems with many LEDs combined with complex optical systems [1]. Such systems allow the integration of additional features and great freedom in vehicle design [2].

The development of high-resolution headlamps is driven by the desire to offer the driver and other road users the best possible visibility in the traffic area. This is achieved by situation-adapted light distributions, which are selected and adapted based on information of the

environment. The light of the headlamps can be generated by switchable pixels, like in video projectors.

Depending on the desired light function, different resolutions and numbers of pixels are needed. A glare-free high beam requires a lower resolution than an information projection on the road [3]. For the realization of such headlamps various technologies are available, each of which makes different demands on the optical system. These technologies are analyzed in detail and evaluated with regard to their potential for use in vehicle headlamps.

2 System requirements

Adaptive lighting functions place different demands on high-resolution headlamps. The most discussed requirements in the literature are the resolution, respectively, the number of pixels, and the contrast. Other requirements such as the maximum illuminance or the opening angle do not differ significantly from the requirements of conventional headlamps and are defined by UN regulations.

2.1 Number of pixels/resolution

The term *resolution* in video technology indicates the size of a pixel matrix. The term *pixel aperture angle* indicates how large the solid angle of a single pixel is. The two quantities are often used as a synonym in the context of high-resolution headlamps [4].

Jahn analyzes the necessary resolution for the exemplary lighting functions *glare-free high beam* and *traffic sign masking and marking*. To prevent oncoming traffic from glare, Jahn gives a necessary resolution of less than 3° . For masking traffic signs, a value of 0.1° is given [4].

Moisel postulates that the resolution of a light function is not only determined by the number of pixels of the headlamp but also by the quality of the optical system (modulation transfer function). This is an important factor, as for reasons of cost, no high-quality lenses as in video projectors can be used. Moisel gives a reasonable resolution of 0.05° per pixel [5].

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Gut et al. analyze in detail the necessary resolution for a headlamp with a micromechanical mirror in combination with a laser light source. This type of headlamp has no individually switchable pixels, but is based on the deflection of a light beam [6].

Hummel shows that a resolution of 0.1° is sufficient for a glare-free high beam in many scenarios [7].

Brunne et al. assign the required resolution for 17 different light functions. The scale ranges from approximately 0.03° (project animated navigation information on the road) up to 1° (individual light patterns) [3].

Reinprecht et al. analyze the influence of the relationship between the factors: radius of curvature, distance between the vehicle and the masked object, speed, and latency. Based on this analysis, Reinprecht et al. are able to make a statement about the necessary resolution for different situations. As useful resolution for most scenarios, Reinprecht et al. give a value of less than 0.02° [8].

2.2 Contrast

The definition of contrast depends on the considered type of light function. For example, the contrast of a glare-free high beam or marking light is calculated differently from the contrast of an on-road projection.

Moisel assumes for a glare-free high beam a maximum illuminance of 120 lx and 0.5 lx in the masked area. The illuminance of the masked area is based on the UN Regulation ECE112 [9]. Moisel gives a definition of a global contrast C_g with the brightness of an on-pixel B_{on} and of an off-pixel B_{off} :

$$C_g = \frac{B_{\text{on}}}{B_{\text{off}}} \quad (1)$$

The resulting minimum contrast C_g for a glare-free high beam is 240. Furthermore, Moisel defines a factor to describe the brightness gradient of the cutoff line.

Jahn et al. perform a study to analyze the optimal contrast for projected symbols. The subjects adjust the brightness of the projected symbol at a given ambient luminance. The mean contrast decreases with increasing luminance, with the maximum contrast being 3 (Weber contrast). The preferred contrast of the individual subjects has the same tendency, but has a different base line. The recommendation of the authors is, therefore, to let the driver set his personal base line for the projection of symbols [10].

2.3 Requirements for an ideal headlamp

The technical requirements for high-resolution headlamps cannot be given as a general value because they depend on the light functions to be implemented. The choice of the main components of a high-resolution headlamp, the light source, and the image modulator are, thus, determined directly by the desired light functions. Based on the analyzed literature a resolution of 0.05° is reasonable to realize most light functions.

3 System components

The components of one possible hardware configuration for a high-resolution headlamp are shown in Figure 1 [11]. Sensors detect the vehicle environment and the vehicle condition. Based on this, the information processing block generates a suitable light distribution, which is converted by the control unit into commands for the image modulator and the light source. The image modulator is an optomechatronic device that is able to spatially modulate light (see Section 3.2). In additive systems, the image

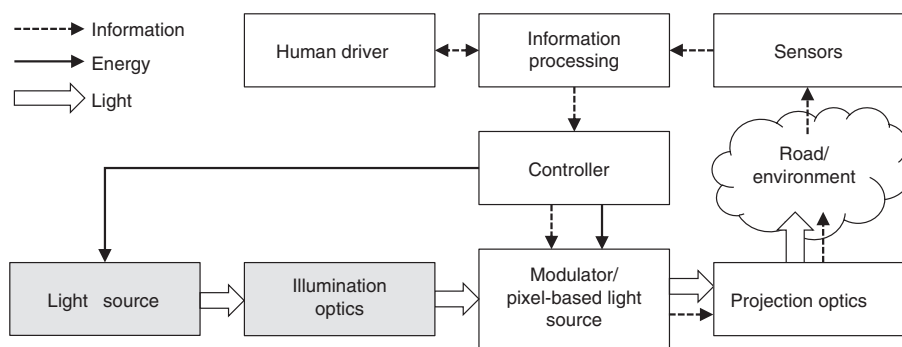


Figure 1: Components of a high-resolution headlamp [11]. White boxes: additive system. White and gray boxes: subtractive system.

modulator is a pixelated light source; therefore, the two gray boxes are not needed. In subtractive systems, the image modulator is illuminated by a separate light source, which requires an illumination optics.

3.1 Light source

A specific light source cannot be defined as the most suitable, but depending on the application, different light source types, as well as different numbers and arrangements, are advantageous. Therefore, in Table 1, an overview of several automotive compatible light sources is given.

Historically, the automotive industry most frequently use halogen and gas discharge lamps, which emit light into the 4π -space and typically provide high luminous flux [2]. The halogen lamp (H7) Osram Silverstar 2.0 (OSRAM GmbH, Munich, Germany) and the gas discharge lamp Osram Xenarc 66240 XNB are exemplary listed. Assuming that the light-emitting surface of the halogen lamp can be calculated from the area of the enfolded cylinder of the filament, the emitting surface is 4.0 mm^2 . The size of the arc of the gas discharge lamp is similar to the size of the halogen lamp. The emitting surface is, therefore, assumed to be 4.0 mm^2 as well [12]. The light sources provide a luminous flux of $1500\text{--}3200 \text{ lm}$ [13, 14].

In contrast, more efficient semiconductor-based light sources such as LEDs or laser diodes emit in a 2π -hemisphere, typically with lower luminous flux. For compensation, a plurality of semiconductor diodes can be connected in an array. As examples, the LED Osram Ostar LE UW U1A5 01 and the Laser Osram μ LARP 1 generation are listed. The Osram Ostar LED provides a higher wall-plug efficacy (WPE) than the 4π radiators but emits a lower luminous flux despite a larger emission area using a five-chip arrangement [15]. For the μ LARP, multiple luminous flux values are given by Fiederling et al. based on the evaluated size of the emission surface. The global surface provides a luminous flux of 150 lm , while the center is emitting 50 lm over an area of 0.07 mm^2 [16]. Therefore,

the flux per area varies over the light-emitting surface, too, and reaches up to 714 lm/mm^2 in the center. Osram states a luminance of up to 511 cd/mm^2 for the μ LARP [16]. The luminance of conventional light sources is much lower, for gas discharge lamps around 200 cd/mm^2 , and halogen H7 powered by 55 W offers around 20 cd/mm^2 [17].

Because of the different emission angles and surface areas, the light sources also differ in étendue. The étendue is defined by the refractive index of the surrounding medium n (mostly air), the light emitting surface A , as well as the emission angle θ [18]:

$$G = n^2 \cdot \pi \cdot A \cdot \sin^2(\theta) \quad (2)$$

and can be used to design a suitable illumination optics for the specific modulator [19].

An ideal headlamp combines high luminous flux per emitting area and low emission angle. As gas discharge lamps offer a high flux per area but emit in a 4π -space, this results in large optical systems for concentrating light. LEDs emit approximately the same flux per area as halogen lamps but project in a much smaller angle. The same applies for laser diodes.

In principle, the more directionally the light emission takes place, the better the high-resolution technology can modulate it. Accordingly, semiconductor light sources for image modulators are preferable. Furthermore, the 2π emission must be focused on the image modulator with suitable illumination optics (see Section 3.3).

3.2 Modulator technologies

The main component of a high-resolution headlamp is the image-generating element, which is responsible for the high resolution of the light distribution. The different technologies are explained in detail in Section 4.

For the classification of the technologies, two different types are established. Gut et al. and Kloppenburg et al. propose the classification on the left in Figure 2 where the technologies are subdivided according to the

Table 1: Overview of light sources for automotive headlamps by Wolf [12].

Light source	Halogen (H7) Osram Silverstar 2.0	HID (D2S) Osram Xenarc 66240 XNB	LED Osram Ostar LEU W U1A5 01	Laser Osram μ LARP 1. Generation
Luminous flux Φ in lm	1500	3200	2125	50/150
WPE in lm/W	27	91	137	36
Emission angle θ in sr	4π	4π	2π	2π
Emission area A in mm^2	4.0	4.0	5.5	0.07/2.0
Flux per area lm/mm^2	375	800	386	714/75

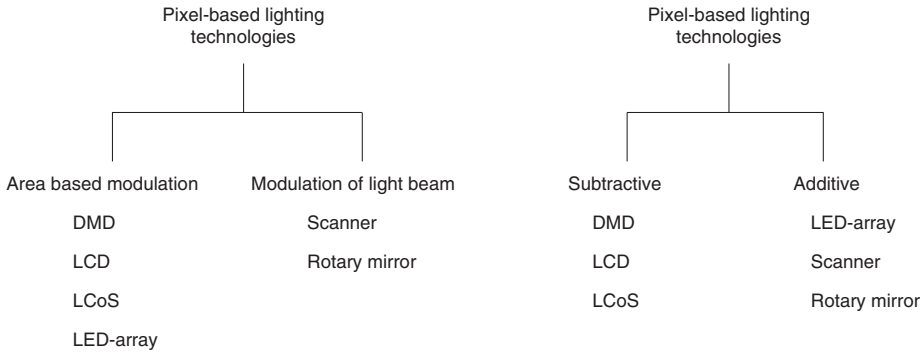


Figure 2: Classification of modulator technologies. Left: according to Gut et al. and Kloppenburg et al. [20, 21]. Right: according to Moisel [5].

type of image generation [20, 21]. Area-modulated systems consist of individually switchable pixels. In beam-modulated systems, a single beam of light or beam bundle is deflected to form an image point by point.

The second way to classify high-resolution technologies, proposed by Moisel, is to subdivide into additive and subtractive modulators (see Figure 2 on the right) [5]. The additive generation of light distributions uses a light source, which is only switched on where a pixel is to be generated. An example of this are LED arrays. The scanning technologies can also be understood as additive modulators. In contrast, subtractive systems consist of a permanently switched on light source in combination with a light modulator, which deflects or absorbs light of unused pixels. Examples of these modulator technologies are LCD (liquid crystal display), LCoS (liquid crystal on silicon), and DMD (digital micromirror device).

The high-resolution modulator technologies are compared in Table 2. While all area-modulated technologies can be used largely independent of the light source used, the beam-modulated technologies rely on laser light sources due to the low étendue. With LCD and LCoS, it makes sense to use light sources that emit polarized light (e.g. R/G/B Laser), as no losses are caused by a polarizing filter.

Headlamps with subtractive modulators can generate very high resolutions with 30 000 pixels to over 1 000 000 pixels [23, 24]. The resolution of LED arrays and scanners is typically limited to a few thousand pixels [22, 25, 26]. In contrast, the system efficiency of high-resolution headlamps with additive modulators is inherently higher because neither a specific polarization of the light is required, nor does the modulator need to be completely illuminated. The difference in efficiency becomes apparent in light functions where only a small part of the modulator surface is used for light distribution (e.g. in the projection of a low beam distribution) [11].

LCD and LCoS have the lowest contrast ratio because the liquid crystal cells are not 100% absorbent. The contrast ratio of DMDs is also reduced by reflections at the mirror edges, but is higher than for LCD and LCoS. LED arrays, as well as the scanning technologies, offer, in direct comparison theoretically, the highest contrast, as light can be partly switched off [22].

3.3 Illumination optics

The aim of the illumination optics is to concentrate light of the light source in a desired manner on a subtractive

Table 2: High-resolution imaging technologies [22].

	Technology	Light source	Resolution	Contrast	Efficiency
Area-based modulation					
Additive	Array of diodes	LED/LD	Low	High	High
Subtractive	DMD	LED/LD	High	Medium	Low
Subtractive	LCD	LED/LD	High	Low	Low
Subtractive	LCoS	LED/LD	High	Low	Low
Modulation of light beam					
Additive	Scanner	LD	Variable (high)	High	High
Additive	Rotary mirror	LD	Variable (low)	High	High

image modulator. With the illumination optics, the opening angle and intensity distribution on the modulator can be influenced. This is important because the modulators demand different opening angles. DMDs, for example, require a narrow illumination angle to separate the incoming and outgoing light path [27]. If LEDs are used as a light source, an analysis of the étendue can help to design an efficient system. Ideally, the étendue of the light source G_{LS} corresponds to that of the modulator G_{LM} . In reality, the étendue of the modulator will be the limiting factor for a maximum light output [27]. To calculate the étendue of the light source, the acceptance angle of the illumination optics is considered as the angle θ_{LS} . The acceptance angle of the image modulator corresponds to θ_{LM} . Assuming that the light source is small compared to the illumination optics for an efficient system applies [28]:

$$G_{LS} \stackrel{!}{=} G_{LM}, \quad (3)$$

$$A_{LS} \cdot \sin^2 \theta_{LS} = A_{LM} \cdot \sin^2 \theta_{LM}. \quad (4)$$

If the étendue of the light source is greater than that of the modulator, no more luminous flux is projected onto the road, despite a higher luminous flux on the modulator. If the opposite is the case and the étendue of the light source is smaller than that of the modulator, the system is very efficient. However, the full power of the light source may not be used [27].

3.4 Projection optics

The magnification of an optical system is defined as the ratio between the image size and the real object size. This applies also for the size of the pixels of the high-resolution headlamps. Assuming that the luminous flux of every pixel is independent of the magnification, it is possible to define a relationship between the magnification and the illuminance. With the illuminance on the measuring wall E_{25m} and the illuminance on the image modulator E_{LM} , the magnification of the projection optics β is [11]:

$$\beta^2 = E_{LM} / E_{25m}. \quad (5)$$

In conventional optical systems, the magnification is constant over the entire object area. The aspect ratio of the image is identical to that of the object, and the light intensity distribution also remains constant. If the magnification of the image is changed in the projection optics in a targeted manner, there are advantages that can be

used for the generation of automotive light distributions. With cylindrical lenses, it is possible to stretch the light distribution in one direction to adjust the aspect ratio [27, 29]. A radial distorting projection optics redistributes light from the edges to the center of the light distribution [30, 31]. This concept allows to generate efficient light distributions even with subtractive modulators [11].

4 Modulator technologies and design concepts

The following sections describe published prototypes of high-resolution headlamps, and their properties are summarized in Section 4.7 in Table 3. At the beginning of each section, the functional principle and a typical system architecture for each modulator is explained.

4.1 LED array headlamp

The additive functional principle of LED arrays is based on interconnecting several LEDs to form an individually controllable one- or two-dimensional array. Pulse-width modulation of individual LEDs can be used to create gray levels. Discrete LED arrays, where each LED has its own housing, require at least one optical element per LED to ensure seamless image generation. They typically have one light-emitting surface per LED of approximately 0.5–2 mm² and emit in the high-power variant up to 1400 lm [40].

A promising alternative to discrete LEDs are micropixel LEDs that use chip-on-board technology. An example is the Eviyos LED from Osram, which, despite the significantly lower light emitting surface with an edge length of 115 μm and a LED pixel pitch of 125 μm , emits a luminous flux of about 3 lm per pixel [41]. Currently available patterns with a 32 \times 32 array (1024 pixels) theoretically emit a total luminous flux of approximately 3072 lm.

The schematic structure of a LED array-based vehicle headlamp is shown on the left side in Figure 3 [26, 42]. For this purpose, a LED array is used as light source ①. With discrete LEDs, which cannot be placed infinitely close to each other due to electrical contacts, gaps of several micrometers are created. These are perceivable as intensity differences in the generated light image and can be smoothed to a gapless diffuse emission surface by the use of a primary optics ② [43]. A projection optics ③ project the LED array area into the traffic area. Micropixel LEDs (① in Figure 3, right) have negligibly small gaps of a few micrometers, which means that a primary optics is

Table 3: Properties of published prototypes of LED array/DMD/LCD/LCoS/MOEMS headlamps.

	Light source	Hotspot Illuminance in lx	Horizontal in °	Vertical in °	Contrast ratio	Luminous flux in lm	Integration in headlamp
LED array							
Grötsch et al. [25]	3 × 1024 px LED	100	51	8	N/A	4180	Yes
Möllers et al. [26]							
Trommer et al. [32]	4 × 1024 px LED	110	33	8	N/A	N/A	Yes
DMD							
Roslak [33]	220 W HID	109	±14.5	N/A	1:800	1750	No
Kauschke [34] Design 1	145 W HID	53	±14.8	N/A	1:72	1370	Yes
Kauschke [34] Design 2	2800 lm HID	143(9.5)	±35	±10	1:15	N/A	No
Günther [29] Design 1	4200 lm HID	13(1.2)	±30	±10	1:11	N/A	Yes
Günther [29] Design 2	3200 lm HID	N/A	N/A	N/A	N/A	N/A	Yes
Lee et al. [35]	White LED	40.6	±10	±3	1:240 (FOFO)	500	Yes
Bhakta and Ballard [27]	6 × 370 W HID	259	±32	±11	1:1726	30000	No
Michenfelder [36]	370 W HID	207	±23	±11	1:259 (FOFO)	6600	Yes
Knöchelmann et al. [11]							
LCoS							
Ansorg et al. [37]	4500 mW 6x LDs	N/A	±30	N/A	N/A	N/A	No
Roth and Petermann- Stock [31]	LED	40	±15	±5	1:40 (FOFO)	500	Yes
Hesse [23]							
Duhme and Fischer [38]	White LED	72	30	±5	1:240 (FOFO)	650	Yes
MOEMS							
Kloppenburger [22]	RGB LD	N/A	11.4	6.8	N/A	172	No
Hager et al. [39]	17 W 6x blue LD	213	±6	±3	N/A	1920	Yes

LD, laser diode; HID, high-intensity discharge; FOFO, full on/full off.

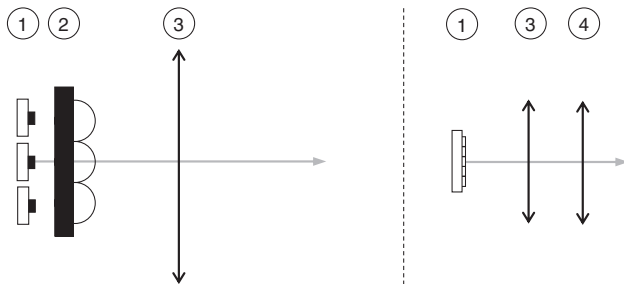


Figure 3: System structure of a LED array headlamp. Left: discrete multi-row LED array. Right: approach with several micro pixel LEDs utilizing two optical systems.

not necessary in most cases. The projection optics often consists of an additional anamorphic lens ④ to adjust the aspect ratio of the projection [26].

Moisel et al. were the first to introduce a LED array that cannot only reproduce conventional lighting functions but also partial masking without moving actuators [44]. In the first prototype, 80 LEDs are arranged in a 4 × 20-pixel array and projected into the traffic area due to the small gaps without primary optics. Despite high light intensities, Moisel et al. criticize the system blur and chromatic aberrations. In a second prototype, the resolution

is increased to 96 LEDs with larger gaps in a 4 × 30-pixel array. In addition, primary optics to increase the sharpness and an achromat are used to compensate the color aberrations. Results are approximately the same light intensities, a clear improvement in sharpness, as well as a chromatic aberration compensation. At the same time, however, the smallest inhomogeneities of the array, e.g. not completely compensated gaps between the LEDs, are visible.

Böke et al. present an 84-pixel LED array (see Figure 3, left), which has been used in series production since 2016 by Mercedes-Benz [43]. It uses a silicone-based primary optics [45], which has one total internal reflection element for each LED. Using microstructures on the first surface of an achromat, the light image is smoothly projected into the traffic area [46].

Takahashi et al. present a LED array with 288 pixels with a variable magnification of the individual LEDs. For this purpose, a 6 × 48-pixel array is used, whereby a resolution of up to 0.05° is achieved in the area of the hotspot. Similar to the work of Böke et al., a primary optics is used to compensate for the LED distances. For the projection optics, five lenses made of different glasses and plastics are used to compensate chromatic aberrations. The field of view can be adjusted via a special magnifying lens.

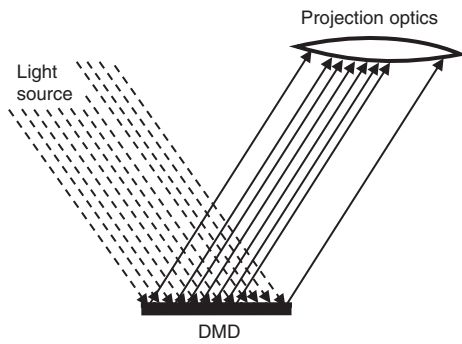


Figure 4: How imaging works with a DMD.

Neither the maximum illumination range nor illuminances are given [47].

The project μ AFS, funded by the German Ministry of Research and Education between 2013 and 2016, involves Daimler, HELLA, OSRAM Specialty Lighting and Opto Semiconductors, Fraunhofer IZM, IAF, and Infineon. The aim of the project is to develop a LED-based light source with which high-resolution lighting functions can be implemented. The result is a micropixel LED array (Eviyos LED from Osram) with 32×32 blue LEDs on which a phosphor is located, and so white light is emitted. The square LEDs have an edge length of $115 \mu\text{m}$ and a pixel pitch of $125 \mu\text{m}$. A maximum of 3 lm are emitted per LED. The total area of the array is $4 \times 4 \text{ mm}^2$ [25, 26].

Möllers et al. describe a first prototype in which three Eviyos LED arrays with a total amount of 3072 pixels are integrated into a headlamp. The optical system consists of four lenses, two of which focus the light and then two cylindrical lenses expand the aspect ratio to about 3:2. The left (right) headlight has a horizontal opening angle of -40° (-11°) to 11° (40°). Vertically, light is emitted in the range of -3° to 5° . In the central area of the light distribution, which is sharply imaged, each pixel has a size of 0.23° vertically and 0.35° horizontally. A drop in light intensity in the range -20° to -40° is generated by the off-axis

arrangement of the third chip. As system efficiency, Möller et al. simulate 45% and measure 43%. Assuming that each LED emits 3 lm, the maximum illuminance is 100 lx with the simulated system efficiency [26].

Trommer et al. describe another prototype with four of the Eviyos LED arrays with a total amount of 4096 pixels. The optical system is non-distorting and consists of three lenses. As with the first prototype, the light distributions of the two headlamps are asymmetrical. The left (right) headlight has a horizontal opening angle of -28° (-5°) to 5° (28°). Vertically, light is emitted in the range of -2° to 6° . This corresponds to a resolution of 0.25° per pixel. In order to generate a standard-compliant light distribution, a base beam for the basic light distribution and white laser modules for the central hotspot are used in addition to the LED arrays. Trommer et al. assume a luminous flux of 3 lm per LED and give a maximum illuminance of 110 lx. Together with the size of the light distribution, a total luminous flux of the system of 5700 lm can be calculated [32].

4.2 DMD headlamp

In Figure 4, the operation of a DMD is schematically illustrated. The individual micro-mirrors are mounted on a hinch so that they can tilt in one direction by a fixed angle. The optical efficiency is determined by the reflectivity of the mirror surface, the transmittance of the cover glass, the array fill factor, and a factor that takes into account losses due to diffraction effects. The factors together give a typical optical efficiency of about 68% [48].

In Figure 5, the two common system architectures are shown [49]. ① denotes the light source, ② the illumination optics, ③ an optional homogenizer, ⑤ the DMD, and ⑥ the projection optics. In Figure 5 on the right is shown the telecentric architecture in which the separation of the incoming and reflected beam is realized by a prism ④. The term *telecentric* refers to the square angle between the DMD

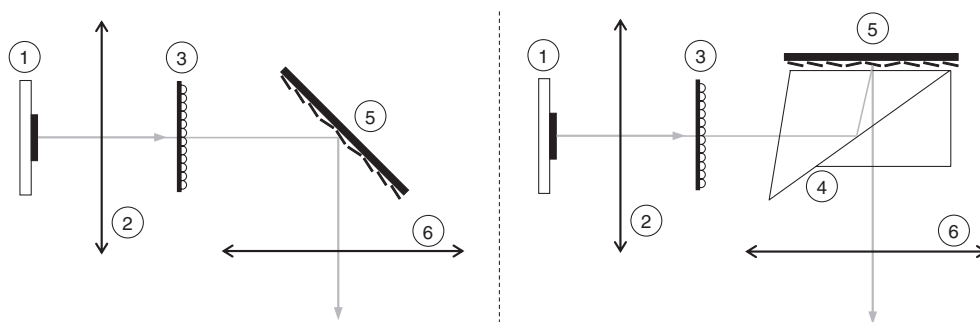


Figure 5: System structure of a DMD headlamp in the two most common system architectures [49]. Left: non-telecentric. Right: telecentric.

surface and the outgoing light path. A telecentric architecture without prism is also possible.

Roslak and Kauschke present a test vehicle with a DMD projector (Design 1). The small opening angle of the system limits the possible light functions, making comparison with conventional headlights more difficult. Together with a lidar sensor, objects in the environment can be detected and shadow cones created for glare reduction [33].

Kauschke introduces an optimized version of the DMD headlamp (Design 2) with a smaller package so that the system can be integrated into a housing of a headlamp [34].

Günther presents a further DMD headlamp (0.7", 4:3). In order to adapt the aspect ratio of the DMD to the aspect ratio of a light distribution, he uses an anamorphic optics with cylindrical lenses. In order to achieve a high illuminance in the middle of the distribution, he illuminates the DMD inhomogeneously. His first concept (Design 1) achieves a contrast of 1:15 in reality. The illuminance that is achieved when masking an object is, therefore, too high (value in brackets in Table 3). The total luminous flux of the prototype is not reported. Günther realizes a second prototype, which is integrated into a headlamp housing. The illuminance at the center of the light distribution of 13 lx cannot meet the requirements [29].

Lee et al. develop a prototype of a DMD headlamp (0.7", 4:3) that replaces the conventional low-beam module. The optical system consists of six lenses. To increase the luminous flux, an additional reflector is integrated with a D1S xenon burner. The authors do not publish information on the resulting light distribution that can be generated with the DMD module. The prototype has a size that allows an integration into a conventional headlamp housing [35].

Bhakta et al. present optical design guidelines for the development of the projection and illumination optics of a DMD headlamp. The DMD (0.3", WVGA) of the prototype presented is inhomogeneously illuminated, using a high-power LED as light source. The projection optics consists of five optical elements with a doublet for color correction and an anamorphic lens to adjust the aspect ratio. The full-on/full-off contrast is measured to 1:240; the contrast for a partial masking is not reported. The total luminous flux is 500 lm, and the maximum luminous intensity is given with 25 380 cd. This corresponds to an illuminance at a distance of 25 m from about 40.6 lx. The prototype is integrated in a headlamp housing [27].

Michenfelder's goal is to create fully adaptive light distribution over a wide range of angles and with high illuminance. He uses six digital projectors, each with a luminous flux of 5000 lm, which are mounted in front of a vehicle

on a rack. The distributions of the projectors are superimposed so that a usable light distribution with a size of $\pm 32^\circ$ horizontally and $\pm 11^\circ$ vertically arises. The system reaches a maximum illuminance of up to 256 lx [36]. When comparing the prototypes to each other in Table 3, it should be noted that the system of Michenfelder generates a light distribution equal to that of two headlamps.

At the Institute of Product Development of Leibniz University Hannover, a DMD headlamp (0.7", 4:3) is realized and integrated into a test vehicle. With a radially distorting optics, the aspect ratio of the DMD is changed so that the desired opening angle of about $\pm 23^\circ$ horizontally and about $\pm 11^\circ$ vertically is achieved. The optical system of the projection path consists of three PMMA lenses. The full-on/full-off contrast is 1:259. The total luminous flux of the prototype without cover glass is 6600 lm with a maximum illuminance in the center of 207 lx. Two of the prototypes can be used in a test vehicle for the evaluation of new light distributions [11, 50].

4.3 LCoS headlamp

Figure 6 schematically illustrates the operation of a LCoS with unpolarized light. The unpolarized light is split up by a polarizing beam splitter. The LCoS changes the polarization in a desired manner of the incoming polarized light and reflects it back into the optical path. Because of the reflective principle, optimized cooling is possible compared to LCDs. With a fill factor of 93%, a resolution of up to $8K \times 4K$ is possible with a contrast of 1:100 [51]. Depending on the LCoS type, the spectrum to be modulated can range from UV to far infrared.

Figure 7 shows on the left side the schematic structure of a LCoS headlight. ① denotes the light source, ②

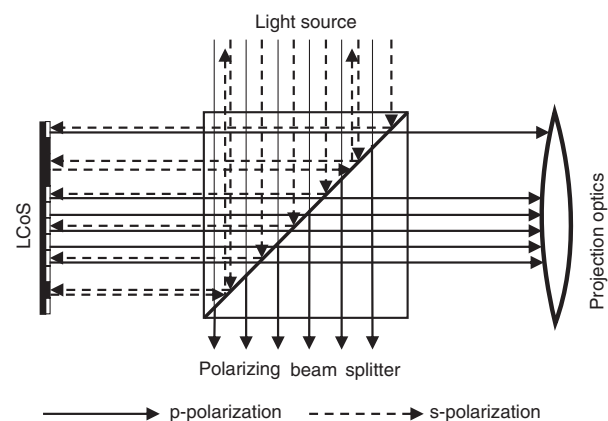


Figure 6: How imaging works with an LCoS.

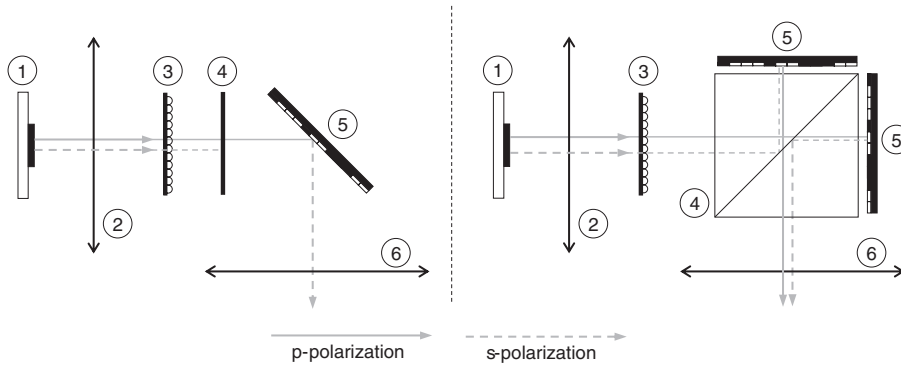


Figure 7: System structure of an LCoS headlamp. Left: using one LCoS. Right: using two LCoS.

the illumination optics, ③ an optional homogenizer, ④ a polarizer, ⑤ the LCoS, and ⑥ the projection optics. A polarizer is required in the beam path in front of or behind the LCoS. As only one direction of polarization can be used, the optical efficiency is thereby halved. If a polarizing beam splitter ④ is used instead of a simple polarizer, two polarization directions can be used with two LCoS.

Roth et al. present an amplitude-modulated LCoS headlamp with a LED as light source. To use both directions of polarization, two LCoS chips are used, which are homogeneously illuminated. In order to generate an automotive light distribution, a distorting projection optics with five lenses is used. As full-on/full-off contrast, a value of 1:40 is given. The prototype generates a luminous flux of 500 lm and a maximum illuminance of 40 lx in an angular range of $\pm 15^\circ$ horizontally and $\pm 5^\circ$ vertically and is integrated in a headlamp housing [31].

Ansorg et al. develop a phase-modulated LCoS headlamp that can generate light distributions of width $\pm 30^\circ$ and colored projections. As light source, six laser diodes are used with a maximum power for generating white light of approximately 4.5 W. The luminous flux of specific light functions and the optical system efficiency are not reported. The full width of the light distribution can be generated with a lens with a diameter of 28 mm. The disadvantages of the system are the low contrast and inhomogeneity of the projection. The prototype without driver electronics and LCoS control has dimensions of $50 \times 150 \times 60 \text{ mm}^3$ and can, thus, be integrated into a headlamp [37]. The optical concept of the phase-modulated LCoS headlamp is described as a patent [52, 53].

4.4 LCD headlamp

An LCD consists of many small switchable elements that change the polarization direction of the light depending

on the switching state. Together with a polarizer and an analyzer, it is possible to selectively switch regions to be absorbing or transmissive (see Figure 8). Because of the operation principle, theoretically, 50% of the input light will be absorbed when using non-polarized light. Additionally, the transmission of an LCD is dependent on the number of pixels. Hesse gives a value of 80% transmission for an LCD with 50 000 pixels [23].

In Figure 9, ① denotes the light source, which can typically be a LED, a LED array, an overlay of R/G/B LEDs, or laser diodes. ② denotes the illumination optics, ③ an optional homogenizer, ④ a polarizing beam splitter, ⑤ a mirror, ⑥ the LCD, and ⑦ the projection optics. In the concept on the left in Figure 9, only one polarization direction is used, whereby the efficiency is halved. On the right in Figure 9, the p-polarization light transmitted by the polarizer is also directed to the LCD or to a second LCD via a reflector. Both directions of polarization can be used, and theoretically, a much higher efficiency is achieved.

As part of the VoLiFa2020 project, the concept of an LCD headlamp is investigated. The result is a high-resolution headlamp that is integrated into a test vehicle. As light source, a 25-pixel LED array is used. The system design of

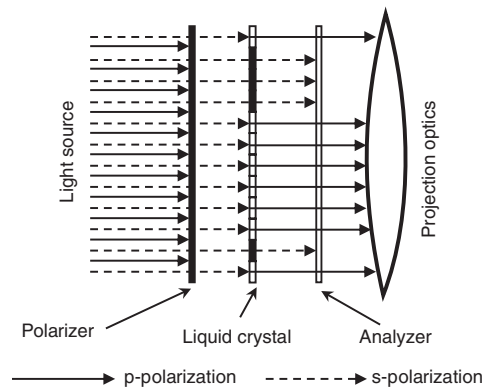


Figure 8: How imaging works with an LCD.

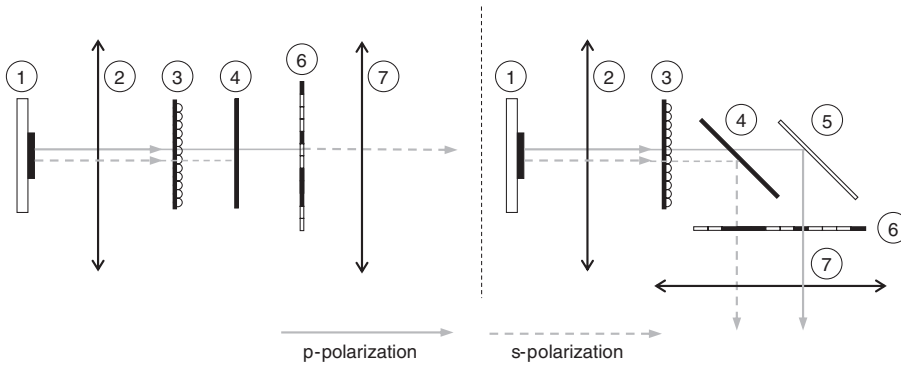


Figure 9: System structure of an LCD headlamp. Left: using one polarization direction. Right: using both polarization directions [54].

the optical path allows to use both polarization directions. The light distribution of the headlamps is asymmetrical and has a horizontal opening angle of -20° (-10°) to $+10^\circ$ ($+20^\circ$) for the left (right) headlamp. The vertical opening angle of both sides is $\pm 5^\circ$. With 30 000 pixels, the LCD achieves a resolution of $0.1^\circ \times 0.1^\circ$. The prototype generates a luminous flux of 650 lm with a maximum illuminance of 72 lx. The full-on/full-off contrast is 1:240. For projections in addition to the low beam, a contrast of 4:1 is achieved [23, 38, 55].

Willeke et al. describe an approach with which the system efficiency can be doubled using a pre-polarized laser light source in a system that uses one polarization direction (left side in Figure 9). For this purpose, three laser diodes in red, green, and blue illuminate the LCD. A micro-lens array is used to homogenize the color superposition [54].

resolution is largely defined by the control principle and frequency. In Figure 10, an example of a quasistatic-resonant control is shown. One axis is driven in the resonant frequency, while another axis is operated directly. Klop-penburg et al. give a detailed analysis of the control principles of MOEMS [21].

To generate white light on the 2D MOEMS ③, R/G/B lasers ① can be used, which are superimposed by dichroic mirrors (Figure 11) [22]. Alternatively, a 1D MOEMS with blue laser diodes and phosphor (LARP) ④ can be used [39]. As the phosphor is placed behind the MOEMS, at least one additional lens ⑤ is necessary.

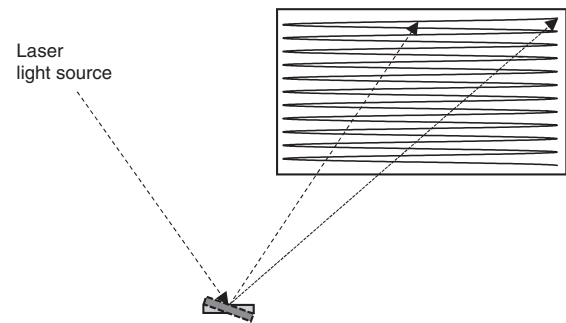


Figure 10: How imaging works with an MOEMS.

4.5 MOEMS headlamp

Micro-mirrors are often referred to as MOEMS (micro-opto-electro-mechanical system). The light of a light source with a small étendue is scanned off the image plane. The

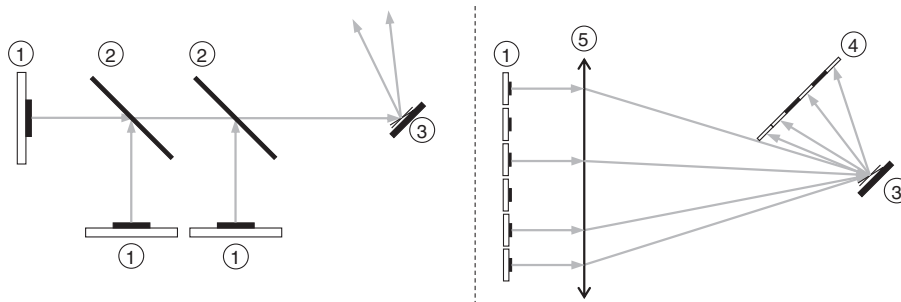


Figure 11: System structure of an MOEMS headlamp. Left: using R/G/B superposition and 2D MOEMS. Right: using LARP and 1D MOEMS.

Kloppenburger presents a projection unit based on a 2D micro-mirror illuminated by R/G/B laser diodes. The micro-mirror is operated partially resonant. Limited by the frequency of the controller, a resolution of 128×64 pixels can be realized. The optical efficiency is 31%. With three laser diodes, a maximum possible luminous flux of 323 lm is achieved; for white light, 172 lm is given. Thus, the system is suitable as a projection module, which allows colored projections in the traffic area [22].

In the iLaS project, which is funded by the German Ministry of Research and Education, Audi, Bosch, Osram, KIT, and ZKW present a scanning laser headlamp. In total, the light of six blue laser diodes with a cumulative power of 17 W is projected vertically onto a single-axis MOEMS. An optical efficiency of approximately 70% is reported. As a scanning strategy, both an approach with maximum sharp vertical lines and an approach of maximum vertical homogeneity are pursued. With the first approach, a maximum luminous intensity of 133 kcd (ca. 213 lx) is reached in the area of the hotspot. In the second approach, a lower intensity of max. 57 kcd (ca. 91 lx) is achieved. Overall, the six laser diodes emit a luminous flux of 1920 lm. The challenges here are the tuning of the laser diodes for homogeneous illumination, as this automatically leads to a reduction in the resolution [39].

4.6 Rotary mirror

Rotary mirrors are based on the principle of a rotating polygonal roller in which each side represents a mirror surface (Figure 12). An incident beam is typically deflected one-dimensionally in different directions, depending on the position of the roller by the mirror surface. For this purpose, a very small étendue of the light source is necessary.

Tatartschuk and Kreuzer describe a two-dimensional rotary mirror, which allows a light deflection in the vertical

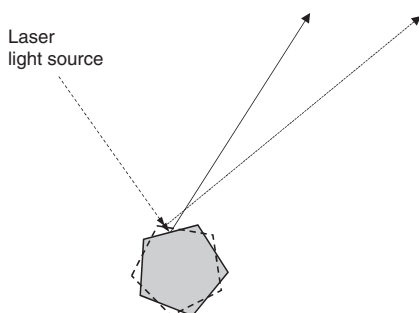


Figure 12: How imaging works with a rotary mirror.

axis [56]. The resolution of the system is largely defined by the number of mirror surfaces.

4.7 Review on high-resolution headlamp prototypes

The following review is based on the published prototypes of high-resolution headlamps and their properties in Table 3.

Because of the currently limited number of pixels, with LED arrays, only the masking of traffic objects is meaningful. The micro-pixel technology has an unexploited potential for optimization in terms of resolution and aspect ratio. With an adjustment of the aspect ratio, the optical system of the presented prototypes of at least four lenses could, thus, be reduced by half. The LED array technology from Böke et al. is ready for series production.

DMDs as modulators are only available in a limited size. As the usable luminous flux is limited by the étendue, gas discharge lamps (HID) are used as the light source. The commonly used 0.7" DMD [48] is not specified for automotive applications. Bhakta et al. present a prototype with a 0.3" [57] DMD specified for automotive applications and uses a single white LED as light source. Because of the DMD size and limited luminous flux, the system can only generate narrow light distributions, such as a partial high beam or a projection module. A second DMD from Texas Instruments (Texas Instruments Incorporated, Dallas, TX, USA), specified for automotive applications, has an aspect ratio of 2:1 and a diagonal of 0.55" [24]. With this chip, a larger luminous flux and a larger angular range than the Bhakta et al. system will be possible. So far, no prototype with this chip has been released. The contrast ratio of the prototypes with DMDs is not sufficient. Although, e.g. for the system of Bhakta et al. a full-on/full-off contrast of 1:240 is reported, however, the contrast for masking or for the cutoff line definitely is well below this value.

The two featured LCoS systems use different approaches for image generation, so a direct comparison is difficult. Compared with the DMD prototype of Bhakta et al., the system of Roth et al. performs well. With a larger horizontal and vertical opening angle, Roth et al.'s system achieves a similar illuminance. With similar luminous flux, this is only possible by the redistribution of light with the radially distorting projection optics used. For the realization of a headlamp with the LCoS module alone, however, the illuminance and the luminous flux are far too low.

The developed LCD for VoLiFa2020 is custom made with adjusted aspect ratio and resolution. By adapting the

LCD and using both polarization directions, the prototype is capable of generating high-resolution light distributions with low complexity and small package. The contrast for a precise masking will be well below the specified full-on/full-off contrast of 1:240. The direct relationship between the number of pixels and the transmission of the LCD module leads to a conflict of objectives, which must be solved for a series development.

The MOEMS-based prototypes currently do not reach the illumination angle necessary to generate a complete light distribution. Kloppenburg, therefore, describes a MOEMS prototype as an additional projection module. The prototype of the iLaS project has with an additional base beam potential for use as a headlamp.

5 Conclusion and outlook

Pixel-based headlamps allow developers to design a variety of new lighting features. The bandwidth ranges from an improvement of current light functions, e.g. a more precise masking of oncoming traffic, to completely new functions such as the projection of content onto the road, which enables communication with other road users independent of transmission protocols and receiver devices. The lighting functions make very different demands on the technical system of the headlamp, which must be taken into account in the development.

One of the next challenges in the development will be to combine different modulator technologies to efficiently realize desired functions. Parallel to this, the future high-resolution lighting functions have to be developed, which, unlike in the past, should not be a selection of ready-made scenarios as in advanced frontlighting systems, but rather dynamically optimized functions for the current visual situation. Furthermore, the acceptance of drivers and other road users will have to be investigated. In particular, for new functions such as projections on the road, the possible distraction and acceptance by the driver and other road users must be examined before an approval.

On the way to a series production of high-resolution headlamps, further challenges need to be solved. Influences on the modulators, light sources, and the complete systems in real driving scenarios like vibration, humidity, and temperature must be analyzed to determine the reliability. Furthermore, for laser-based headlamps, eye safety is an important factor.

In general, a positive effect on traffic safety will only be achieved by these new technologies if market penetration is sufficiently high. Therefore, the use in mobility

concepts, especially with regard to partial/autonomous driving is important. Because of these issues, vehicle frontlighting will be an exciting field of research even after one or more of the technologies presented have been developed to series maturity.

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