High-resolution headlamps: Innovative functionalities and the potential of using laser diodes as light sources

Yang Li*, Marvin Knöchelmann, Roland Lachmayer
Institute of Product Development, Leibniz University Hannover; Hannover, Germany
*Contact email address: y.li@ipeg.uni-hannover.de

Abstract—High-resolution headlamp systems are increasingly attracting attentions from OEMs and researchers, while plenty of innovative lighting functionalities such as precisely glare avoidance of high beam, fully adaptive driving beam and on-road projection bring a huge potential for improving the driving safety and comfort. Besides, as a respond to the trend of intelligent transportation and autonomous driving in the future, lighting based communication between drivers and other road participants is also a possible supplementary functionality of such headlamp systems. The growth of such headlamps raises specific illumination demands regarding to the functionalities consequently.

To achieve these high resolution dynamic light functions and to fulfill the relevant requirements, several additive or subtractive projection technologies are considered by OEMs and researchers. Due to the different applied circumstances and intentions, the uses of these technologies in headlamp systems are different from those in video projectors. Headlamp systems demand a high optical efficiency with highly compact constructions, which raises requirements to the design and arrangement on both mechatronic and optical systems. As a result, particular schemes for different projection technologies have been developing and brought up in recent years.

Moreover, the pursuit of efficiency and compaction suggests the appliance of laser diodes as light sources. Laser diodes have intense optical output power with relatively small emission areas and narrow divergent angles, leading to the use of small optical components for realizing compact modules. Besides, other peculiar properties of laser diodes such as linear polarizations and likely fiber-coupled can be utilized for specific designs as well.

In this article, the development of headlamp systems in Germany with correspondent innovative functionalities and requirements are discussed, prototypes composed of different technologies are illustrated, and furthermore, the advantages of using laser diodes for these technologies are also presented.

Keyword: High-resolution headlamps; lighting based communication; projection technologies; laser diodes

I. INTRODUCTION

Vehicle headlamps were illumination devices that only had the function of enhancing the traffic visibility in early years. Since matrix LED headlamps came out, headlamp systems began to adapt to road and traffic conditions. In recent years with the rapid development of the automotive industry, advanced driving assistant system (ADAS) is put forward as an essential element to improve the road safety and driving comfort, as well as a key technique for autonomous driving. This also leads to the intention change of headlamp systems. The concept to use headlamps to generate high-resolution light distribution to intelligently illuminate the traffic area and to assist drivers, known as adaptive driving beam (ADB), is considered as an important part of ADAS. For the generation of this high-resolution light distribution, different technologies are in discussion in order to find the proper technical route and structure for headlamp applications regarding to functionality, optical performance, regulations and so forth.

The evolution of headlamps also refers to the light source. The light source for headlamps should fulfill the requirements such as high luminance, high efficiency and allowing the use of small optical elements for light manipulation to realize compact lighting modules. The development in semiconductor engineering introduces LEDs and semiconductor lasers into automotive lighting [1]. LEDs have been widely spread in this sector since this technology matures and they meet most demands of headlamp systems. A further step is to use laser diodes (LDs) as the light source. Their characteristic lighting properties have the opportunity to improve the current headlamp systems.

In this paper the features and innovative functionalities of ADB modules will be discussed. The advantages of using LDs as light sources for headlamp applications in different aspects will be presented, as well as the approaches to generate a required white light. At last, the stand of technologies and the art of ADB modules will be demonstrated respectively.

II. FUNCTIONALITIESOF HIGH-RESOLUTION HEADLAMPS

The earliest pixel headlamp concept to replace the conventional vehicle headlamps is the matrix LED array that is composed of multiple independent controllable LEDs and optical elements. Each LED stands for one pixel, creating an illumination channel with the help of the optics to the target area. By dimming or turning off any individual LED, grey scales can be implemented to the related channel, so that the glare-free high beam and the bending light can be realized. Currently LED array headlamps have around 100 pixels due to some design limitations such as restricted space in a headlamp or heat dissipation of the light source module. As implementations of LED arrays, multi-segment LED and micropixel LED (Eviyos LED from Osram) are invented for headlamp applications [2][3]. These technologies allow more precise masking light than conventional LED arrays on the road. Recently, more innovative functionalities of headlamps are brought up in order to adapt to the developing transportation as an important part of ADAS. For example, a light with higher color temperatures has a better illumination performance in normal weather conditions. However, people sometimes have to drive in weather conditions with a limited visibility, such as foggy or rainy days. For these situations, an illumination light with a lower color temperature enables a longer visibility distance than the light with a higher color temperature [4]. Therefor a color temperature steerable lighting device that can be well adaptive to different weathers is helpful to improve the road safety.

Apart from these illumination functions, on-road projection is also considered to be helpful in the ADAS. This functionality allows a driver to acquire information direct from the road and to communicate with other road participants of the driver's decisions and intentions. For example, a headlamp with on-road projection can mark the dangerous obstacles detected by other sensors like Lidars, construct a light barrier with the width of the vehicle, project navigation data on the road for the driver or a zebra crossing for a pedestrian [5][6][7][8]. This lighting-based communication can happen automatically in the future when autonomous driving reaches a higher level and driverless vehicles are brought into operation. Such a function demands a high resolution of the light module, therefore several technologies for video projectors are adopted in headlamps in order to create this high-resolution light distribution. These serviceable technologies will be presented in chapter 4. Furthermore, this projection functionality can even be improved by using chromatic on-road projection. It makes the projection content noticeable not only during the night, but also during the daytime or in some extreme conditions like snow covered roads.

To conclude, an ADB module for future vehicles is a high-resolution lighting device which has the following possible features and functionalities:

- Compact, so that other elements (daytime running light, turning indicator) can be integrated in;
- Bending light;
- Precisely glare-avoidance;
- Generation of the weather-adaptive illumination light;
- Chromatic on-road projection.

III. LASER DIODES AS LIGHT SOURCES

A. *Copmarison between LEDs and Laser diodes*

Although halogen (tungsten) bulbs and HID lamps are still available as light sources for headlamp systems, LED currently dominants the market due to its high efficiency, high reliability, long lifetime and increasingly smaller dimension which is ideal to save space in headlamps [9][10]. However, the power conversion efficiency of LEDs drops with the increase of the input power density, as depicted in Fig.1 (red line) [11]. This feature is a drawback of LEDs to be used in high power applications, such as headlamps. Apart from this, the nearly lambertian emission of the LED's two dimensional emission surface technically limits the propagating luminous flux, this effect relates to the term étendue, which will be explained in section C of this chapter [12]. To improve these situations, LDs which have different performances in these aspects are considered as light sources for headlamp systems since years. Unlike a LED, a LD usually requires a certain input power to start the emission, known as lasing threshold. When the input power density is above the lasing threshold, the output power and the power conversion efficiency of a LD show significant rises [5][11]. The conversion efficiency becomes steady when the input power density reaches a certain degree, implying that the optical output power almost increases linearly with the increasing input power. This behavior is demonstrated as the blue line shown in Fig.1. A dividing line of the input power density locates at the crossing point where the efficiencies of the LED and the LD are the same. On the right side of the dividing line, the LD has a better efficiency than the LED, which indicates LDs are more efficient in high power applications.

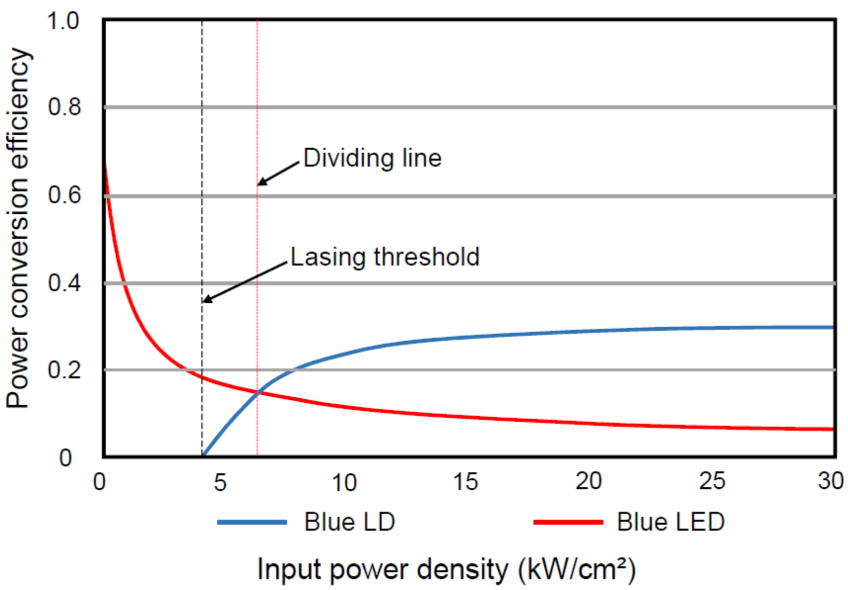

Figure 1. Power conversion efficiency vs. input power density of a blue LED and a blue laser diode at the wavelength of 450nm [11].

B. Laser diode properties

LDs are semiconductor lasers which are available in different packages and sizes with the spectrum range from ultraviolet to far-infrared. Commercial LDs emitting the visible spectrums that are suitable for headlamp applications have the output optical power range from few mW to few Watts. These LDs have similar emission properties as demonstrated in Fig.2 using a TO can laser diode as an example.

A LD has an extremely small emission facet in the shape of ellipse [13]. The output beam has two divergent axes known as fast axis and slow axis, respectively. The laser light along the fast axis has a larger divergent angle than that along the slow axis. The laser beam along each axis has an approximately Gaussian intensity distribution. These 2 axes together result in an elliptical output beam cross section profile. One additional point about the 2 axes is that there is normally a tiny distance between the emission points of these 2 axes which is known as the astigmatism (ΔAs in Fig.2). The value of the astigmatism ranges usually from 3 to 50 µm, depending on the modes of LDs [13]. In some cases where a precise beam shaping is needed, this astigmatism has to be taken into account. The divergency of a laser diode is usually specified as $\emptyset\perp \times \emptyset\parallel$ in optical community, which means the divergent angles along fast axis and slow axis at $1/e^2$ energy level. Or it is also characterized by $\emptyset\perp FWHM \times \emptyset\parallel FWHM$ in LD industry, meaning the divergent angles along the axes at full width half magnitude (FWHM) energy level. The former is about 1.7 times larger than the latter [13].

Laser beam from a solid state LD has one more special property – the polarization direction. The emitted radiation of a LD is linearly polarized and the polarization direction is always parallel to the slow axis as depicted in Fig.2. The polarization ratio varies from 30:1 to 100:1, depending on the mode of the LD. This polarization property can be either an advantage or a disadvantage according to the application.

C. Advantages of using laser diodes in headlamps

As mentioned in the earlier section, a LED has the restriction due to its étendue. Étendue G is a geometry invariant being defined by the emitting surface's area and the emitting angle, which never deceases in an optical system. This signifies that the étendue of an optical system is limited by the optical element which has the largest étendue. Étendue is described as

$$G = \pi A \sin^2 \varepsilon \tag{1}$$

where A is the area of the emitting surface and ε is the emitting half angle of a light source. Equation (1) shows that either a small emission surface or a small emission angle results in a small étendue. A LED has a two dimensional emission surface and the nearly lambertian emission distribution, results in a definite étendue that the other optical elements in the system must have equal or bigger étendues in order to reduce the loss. In contrast, a LD has a tiny emitting facet with an ultra-small area value, which means it has an extremely small étendue as a light source. As a consequence, small elements can be applied to shape the laser light and allow the whole optical system to be compact without compromising on light intensity.

The small étendue and the nearly Gaussian low divergent output radiation also means LDs can be easily coupled with fibers with small diameters. This means the LDs can be posited at somewhere cooler than in the headlamps, and the laser light is guided using fibers from the remote position to the headlamps. This method is presented as Remote-Laser-Light source in [14], and can significantly save space in headlamps.

Besides from the geometry aspect, the high output power intensity of LDs also provide improved visibilities to drivers by the long illumination distance. This has already be testified by the series headlamps on Audi R8 and BMW i8.

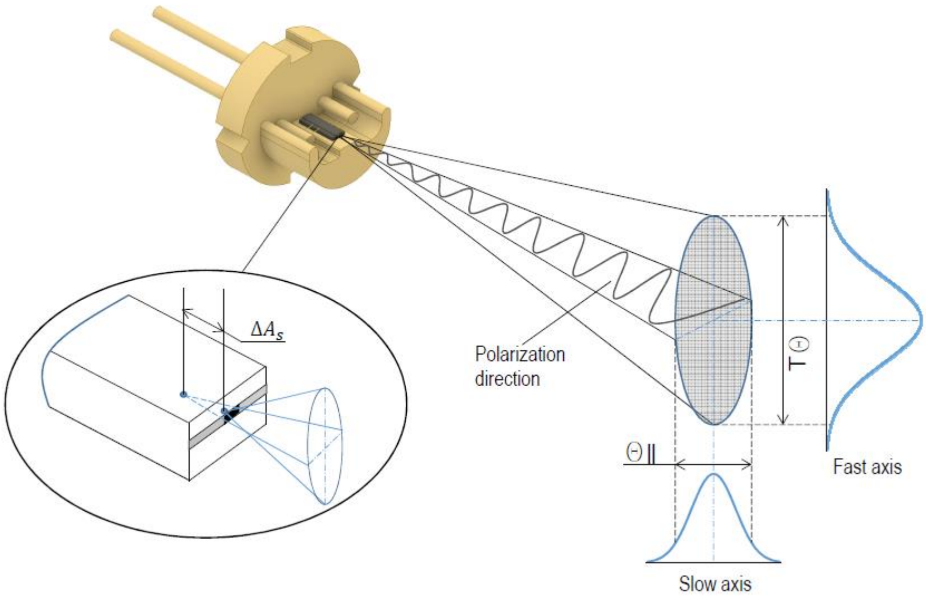

Figure 2. Laser diode emission properties. The beam divergency is specified as $\emptyset\perp \times \emptyset\|$ since this is more frequently used in laser collimation. The astigmatism and the polarization direction can also be seen in the diagram.

D. White light generation using laser diodes

Headlamp systems have to fulfill the regulations in terms of generating white light. Three possible approaches of utilizing LDs to achieve white light are shown in Fig.3 accordingly [10][15]. A and B show the method of converting short wavelengths to longer wavelengths using phosphor layers. A yellow phosphor converts a part of the incident blue laser light to yellow or orange, combining with the unconverted blue laser, a white light is generated (A), this is also the principle of most white LEDs. One advantage of using this method compared to using LEDs is that the phosphor layer can be posited apart from the LDs with a distance, while for a LED the phosphor layer has to be close to the emission surface. This concept is known as remote phosphor that can help the temperature control and allows less restricted layouts in laser-phosphor based systems than using the white LEDs [1][16]. This realization of the remote phosphor concept is due to the relatively small emission divergency and the Gaussian distribution from LDs. Alternatively, the light source can be instead of ultra violet (UV) LDs, and a blend of phosphors can convert all the coming UV radiation into different colors, and a white light can be produced by mixing these colors (B). The other possibility is to mix colored light using at least two LDs, by adjusting the output power of each diode both colored effect and white light can be realized. Since the regulation requires a certain amount of red light to guarantee a color-rendering index for the vehicle front lighting, red, green and blue (RGB) light are usually considered to be combined to generate suitable white light with a broad color space (C) [17]. In this way, a color temperature steerable white light is also possible.

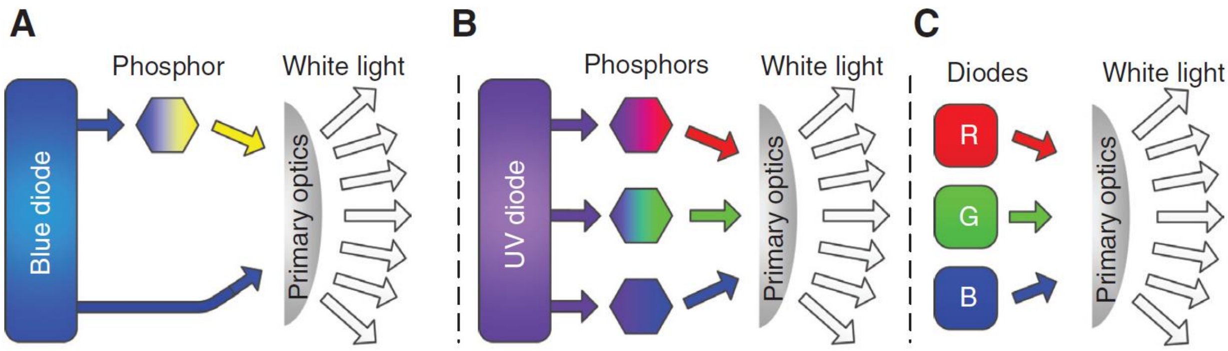

Figure 3. Methods of using laser diodes to generate white light. (A) Mixing blue laser and the phosphor converted yellow light; (B) Mixing all phosphor converted light from UV laser and multiple phosphors; (C) Mixing laser light from plural diodes with different wavelengths (e.g. RGB) [10][13].

IV. TECHNOLOGIES

The figure below shows the system structure of a high-resolution headlamp. Sensors record environmental and vehicle data to determine the current traffic situation and vehicle condition. Subsequently, the calculation of the currently required light distribution takes place in the box information processing. A controller converts the desired light distribution into nominal values for the light source and the modulator. The illumination optics collects the light of the light source and illuminates the modulator. The modulator generates e.g. by deflecting unneeded light rays (principle of the Digital Micro-Mirror Array) the high-resolution image, which is then imaged by the projection optics in the traffic area.

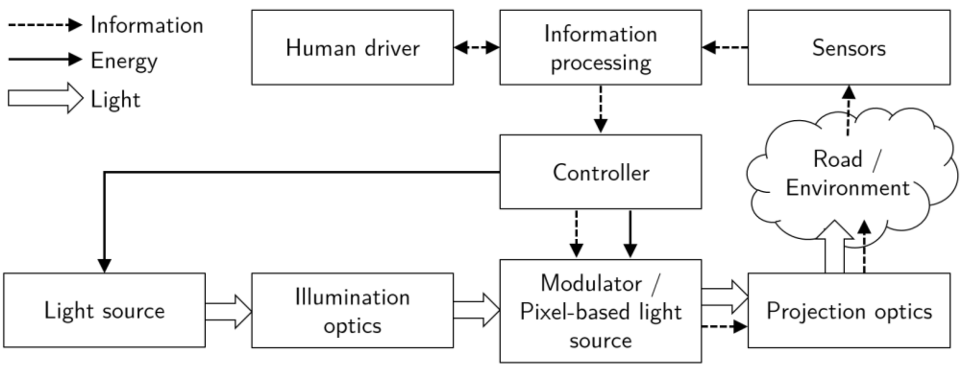

Figure 4. Components of a high-resolution headlamp [8].

Different technologies can be used to generate the high resolution of the light distribution (Fig.5). The following sections explain how these technologies work and highlight the potential of LDs as light sources.

A. *Scanning Micro-Mirror*

By deflecting a narrow beam of light through a single two-dimensional micro-mirror, a high resolution image is created. A single pixel is created by turning on the light source exactly when the micro-mirror deflects the light beam in the desired direction. For the driver or other viewers, the rapid repetition of the sequence gives the impression of a static picture. For the control of the mirror different strategies can be pursued, which Kloppenburg describes in detail [5]. The achievable resolution depends on the maximum frequency with which the mirror can be tilted as well as the maximum frequency with which the light source can be switched. The smaller the mass of the mirror and the suspension, the higher the frequency of the movement of the mirror and thus the resolution can be. For a scanning micro-mirror, therefore, LDs are very well suited as the light source, since the mirror surface can be small because of the low étendue of the LD. Kloppenburg introduces a projection unit for the on-road projection of symbols using this technology and uses three LDs (red, green, blue) overlaid by dichroic mirrors for white and colored projections[15]. Hager et al. use a single micro-mirror in combination with six blue LDs in a high-resolution headlamp, generating white light through phosphorus conversion [19].

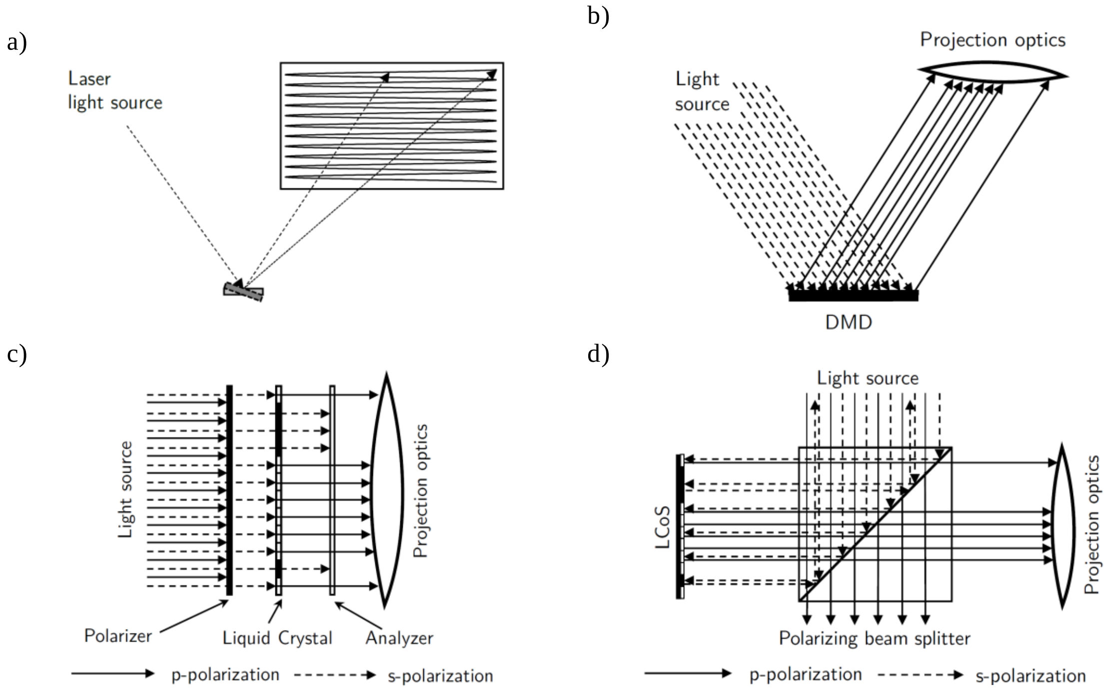

Figure 5. How imaging works with different high-resolution modulators. a) Scanning Micro-Mirror. b) Digital Micro-Mirror Array (DMD). c) Liquid Crystal Display (LCD). d) Liquid Crystal on Silicon Display (LCoS) [18].

B. *Micro-Mirror Array*

A Micro-Mirror Array consists of up to more than 1 million individually switchable mirrors within an area and is typically referred to as a Digital Micro-Mirror Array (DMD). A typical application of DMDs are video projectors, currently DMDs are increasingly used as an image modulator in head-up displays and in headlights [20]. In contrast to the Scanning Micro-Mirror, the mirrors of a DMD can be switched only in two states. In the ON state, the light of the light source is reflected to a projection optical system and thus reaches the image space. In the OFF state, unneeded light from the light source is directed into an absorber, so that the corresponding pixels can be switched off. By switching the mirrors at a high frequency with pulse width modulation, the light intensity of a pixel can be controlled. The étendue of the DMD is determined by the tilt angle of the mirrors, which is typically between 10° and 15°. The opening angle of the incoming light bundle must not be greater, so that the light path of the ON state can be separated from that of the OFF state. The light source used are LEDs, LDs and gas discharge lamps. In most of the published prototypes of high-resolution headlamps with DMD, gas discharge lamps are used as the light source [18]. These have the highest luminance in comparison to LEDs and LDs [16]. The use of high power LEDs with very high luminance as a light source is also promising [21][22]. A prototype with LDs as a light source has not yet been published. Because of the high luminance of LDs it is expected that such a concept can have advantages over the previously published systems.

C. *Liquid Crystal Display and Liquid Crystal on Silicon Display*

Liquid crystal displays (LCDs) are, like DMDs, area-based lighting modulators used in video projectors, but are also used in computer or mobile phone screens. The operation of an LCD is based on the ability of specific crystal structures to change the polarization of light. Figure 4c shows the principle for white unpolarized light. This encounters a polarizer located in front of the LCD. The p-polarized light in the case shown is absorbed, the s-polarized light impinges on the LCD. By applying a voltage, the polarization direction of the incoming light can be changed for individual pixels. Through a second polarizer that acts as an analyzer, only one of the polarization directions is transmitted. Pixels whose light is s-polarized and absorbed appear dark. Liquid Crystal on Silicon (LCoS) displays are different from LCDs in that the light is reflected directly behind the layer of liquid crystals. The structure shown in Figure 4c with a polarizing beam splitter (PBS) fulfills the same function as the described structure of the LCD with two polarizers.

The optical efficiency of the two systems is composed of the transmittances of the two polarizers or the polarizing beam splitter and the LCD or LCoS. In addition, approximately half of the unpolarized light of the light source, namely the p-polarized light, is already absorbed in front of the modulator or moved out by the PBS. The optical efficiency is thereby significantly reduced. In the project VoLiFa2020 this problem is solved by using two LCDs in order to use both polarization directions of the incoming light [23][24]. With LDs, the described problem can also be avoided, since the emitted light is already polarized to a large extent. Therefore an efficient LCD system can be developed with LDs. A prototype of a high-resolution headlamp with an LCD and LDs as a light source has been published in [25], and Ansorg et al. present a prototype of a high-resolution headlamp with an LCoS modulator that uses six LDs as the light source [26].

V. SUMMARY AND OUTLOOK

Headlamp systems are increasingly developing with novel lighting functionalities to support the transportation, meanwhile the intention of a headlamp is extending. Headlamps in form of ADB modules are going to be an important part of ADAS to improve the traffic safety and comfort in a variety of road conditions. However, these lighting based functionalities can also cause distractions of all road users. Thus further investigations regarding to the responses of the masses to these functions in real situations have to be carried out.

The pursuit of the flexible design and high efficiency for automotive applications suggests the use of LDs as light sources. The general advantages of LDs for lighting purposes are analyzed in this article, together with the methods to create the required white light. Although using laser as the light source brings the possibilities for improving the performance of headlamp systems, laser safety for public lighting has to be taken into account before it comes into service.

Several technological solutions to realize the lighting functionalities which are presented and analyzed in this paper, with the potentials and advantages in combination with LDs. Each of these technologies has its own technical capacity and requirement. Thus before employing any of them, factors in terms of cost, applying circumstances, required functionalities have to be taken into account.

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