DE GRUYTER Adv. Opt. Techn. 2016; 5(2): 147–155

Research Article

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High-resolution vehicle headlamps: technologies and scanning prototype

DOI 10.1515/aot-2016-0001
Received January 4, 2016; accepted February 7, 2016; previously published online March 8, 2016

Abstract: The introduction of adaptive front lighting systems for vehicles has increased road safety and drivers' comfort significantly within the last years. A next step in this development is the realization of higher resolution systems to further increase the functionality of vehicle headlamps toward fully adaptive front lighting systems. In this paper, we present a short overview on highly dynamic front lighting systems and the essential technologies for their realization. Different approaches are compared and evaluated regarding their applications for headlamp systems. As an example for on-road projection systems, a laser-based scanning unit is set up and evaluated.

Keywords: high-resolution front lighting; laser diodes; laser scanning unit; solid state lighting.

1 Introduction

The development of vehicle headlamps was influenced by two main factors over the past decades. On the one hand, lighting units were designed with smaller output surfaces and sharp contours, which represent a general trend in design and also allow a better integration into the vehicle front [1]. On the other hand, new light functions increase road safety. While the functionality of cornering light is known for nearly 100 years, AFS headlamps (Adaptive Front-lighting System) are available since 2006. Apart from the basic light distributions for low and high beam, they provide specific road illumination scenarios for many situations, e.g. a narrow beam for motorways, which is more focused than the conventional high beam. Switching between those light patterns is done automatically [2]. A camera integrated into the vehicle recognizes oncoming and preceding traffic to dim down or switch off the high beam and, thus, avoid glare. Further development led to a new headlamp system called 'matrix beam' and was first presented in the Audi A8 [3]. It consists of many LEDs all separately controllable to address specific parts of the light distribution individually. Modules consisting of 50–100 LEDs allow the permanent use of high beam while turning off the light in certain areas on the road to minimize glare.

A next step in headlight development is the realization of high resolution 'pixel light' systems, to provide a functionality similar to video projectors on the road. Such headlamps can address 100 000 or even more pixels individually, outperforming the flexibility of matrix beams by far. The goal is to offer a freely adaptable light distribution perfectly fitting for a particular situation or even depending on the driver and, thus, to increase road safety. To avoid glaring other traffic participants, camera information can be used to detect oncoming and preceding traffic. Also – if properly detected – pedestrians and animals can be highlighted to warn the driver. The intensity of the light can be controlled for each pixel individually, so dark areas can be illuminated to increase contrast while reflections due to road signs, etc., can be reduced by dimming down the light in that area. As pointed out by Jürgens, significantly more pixels are necessary for this functionality than today's matrix beam systems provide [4]. Such a high-resolution headlamp system is fully adaptable to each particular driver, taking into account the age-dependent eye sensitivity and glare susceptibility by providing a selection of different illumination scenarios.

Apart from optimizing the light distribution of the headlight system, another approach is the projection of additional information onto the road at a distance of 10 m–25 m in front of the car. This opens up the opportunity to provide the driver with information relevant to their respective situation

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(navigation information, warnings, etc.) without the need to turn the eyes (and attention) away from the street. Today, information is mainly displayed in the car dashboard where the driver needs to readapt his eyes each time he switches between road and displayed information. An improvement to this situation is provided by head-up displays, which already show relevant data in the driver's field of view. However, it is still necessary to adapt the eyes. When projecting directly onto the road, there is no need for the driver to refocus. Additionally, a so-called contact analog projection is possible. Here, the information is adapted according to the surroundings, for example, by directly highlighting the lane to switch to or the turn to take.

1.1 High-resolution vehicle headlamps

High-resolution headlamp systems or 'pixel light systems' can be divided into two general approaches: 'symbol projection' and 'fully adaptive headlamp'. Symbol projectors overlay an existing light distribution with additional information like text or icons. Possible functions are, for example:

- Projection of navigation data
- Dynamic lane assist (display of vehicle width for narrow passages)
- Projection of warnings, road signs, and car's status information

The required luminance such a system has to generate on the road depends on the luminance of surrounding areas. In order to project detectable information, the luminance generated by the pixel light has to be at least L_p=0.013 cd/m^2 for dark areas (surrounding luminance L_s=0.02 cd/m^2). This value is nonlinearly increased up to L_p=0.4 cd/m^2 for better illuminated areas (L_s=10 cd/m^2) [5]. While it is not allowed by today's regulations of the ECE (United Nations Economic Commission for Europe), the projection of colors with such systems can be very helpful. It is easier for the human eye to detect colored symbols in bright (white) surroundings [6]. The projection of colors also allows a better detection and quicker understanding of the information due to the association with well-known symbols. The color red, for example, is commonly associated with warnings and can be used to make the driver aware of potential dangers.

Fully adaptive headlamps offer the possibility to adjust the intensity of each part (pixel) of the light distribution individually. Possible functions are, for example:

- generation of a contrast-adaptive light distribution
- avoiding glare of oncoming traffic and self-glare due to reflections
- adapting the light distribution to the drivers needs
- projection of additional information

Taking into account the system efficiency and complexity, recent concepts of pixel light headlamps are based on white light and do not offer the possibility to project colored information. Depending on the specific system setup, it may be difficult to further increase the illuminance for the projection of information. Therefore, some concepts are based on subtractive projection, generating dark pixels to project symbols [7].

1.2 Light sources

There are five important factors characterizing a light source and its use for high-resolution vehicle headlamps:

- Luminous flux Φ
- Size of the emitting surface A
- Solid angle of emission Ω (divergence of the source)
- Maximum switching speed
- Color

The luminous flux defines the amount of light generated by the headlamp. Owing to the efficiency of the system, the light output of the adaptive headlamp is significantly lower than the luminous flux of the source.

The size of the emitting surface and the solid angle of emission define an invariant of the system, the so-called étendue G, which never decreases in an optical system. It is

$$G=\pi\ A\ \sin^2 \varepsilon$$

for a light source with emitting surface A and half angle of emission ε in both directions. The solid angle of emission is, in this case:

$$\Omega=2\ \pi(1-\cos\ \varepsilon).$$

This expression shows that a small étendue requires either a small emission surface or a well-collimated light source. Light sources with a low étendue can be concentrated on small surfaces with a small angle of acceptance. This is important for digital mirror device (DMD) systems and much more for scanners, which require a very low étendue. Owing to the fact that the size of the emission surface is directly associated with the luminous flux, a low étendue typically leads to a low luminous flux of the source.

Another important aspect for all systems changing the emission pattern by dimming down or turning off the source is its maximum switching speed. This is especially relevant for scanning systems. When setting up DMD or LCD (liquid crystal display) systems, this value is not necessary as the light source is fully turned on all the time.

While fully adaptive headlamps have to fulfill ECE regulations regarding the emission of white light, the projection of colored symbols is a new approach and currently not allowed by regulations. There is a broad variety of LEDs, HID lamps, and tungsten bulbs available, all emitting white light according to the requirements, whereas some effort has to be made in order to receive white light using laser diodes. Owing to LEDs and laser diodes both being semiconductor light sources, laser-based white light generation can be achieved accordingly. The following two approaches for laser-based white light can be used:

- Mixing colored light of at least two diodes. By using three or more diodes, a system for symbol projection in adaptable colors as well as white can be realized. For illumination of objects, a good color rendering might be important and has to be kept in mind.
- Converting short wavelength light using a phosphor. UV or blue radiation is converted to light with longer wavelengths. When using blue diodes, a mixture of the converted yellow and the original blue light is emitted combining to white light. This is the principle of most white LEDs. Using a UV diode, all the radiation will be converted.

The emission wavelengths of laser diodes are in a very small band around the peak wavelength so they can typically be regarded as monochromatic. When projecting images and symbols, this usually is not a problem, whereas for illumination purposes, the color-rendering index (CRI) is important. Therefore, a minimum amount of red light ($610\ \text{nm} \leq \lambda \leq 780\ \text{nm}$) is required by the ECE regulation 112. This guarantees the correct color perception of red traffic signs. For that reason, at least one diode has to emit light in the required range when using a combination of laser diodes.

It is challenging to generate a specific color of light using a combination of laser diodes due to the necessary alignment and their specific output behavior as shown in Figure 1. Lasers are operated at a constant current showing a significant rise of output power above the so-called 'lasing threshold'. Below this value, the emission is negligible while above it is nearly linear. The lasing threshold strongly depends on the diodes' temperature, which is difficult to keep constant in automotive applications. This makes the precise adjustment of a specific color combination challenging.

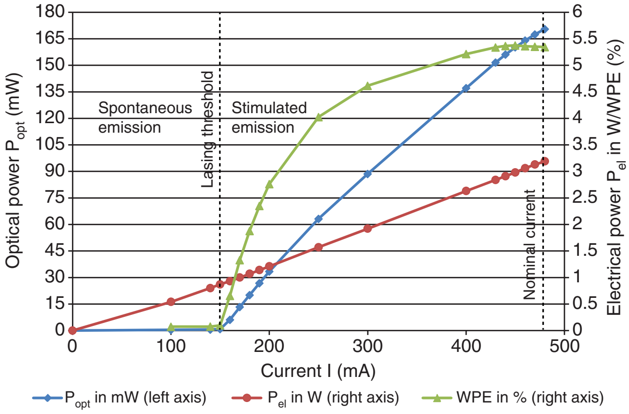

Figure 1: Optical output power and WPE vs. driving current characteristic of a green laser diode at fixed case temperature [8].

2 Technologies for very high-resolution systems

In this chapter, we present different technologies that can be used to realize an adaptive headlamp system. The ideas can be subdivided in area-based technologies, addressing each part of the light distribution simultaneously, and those generating the light distribution sequentially (Figure 2).

2.1 Multiple single LEDs with individual optics

Many of today's LED headlamp systems consist of single LEDs or arrays of up to five LED chips in combination with a lens to shape the light as desired. Putting together many of those light sources each with adapted optics leads to the final light distribution on the road. Switching on and off the single LED chips is used to illuminate or dim out certain parts of the road. This is the principle of a matrix beam as mentioned in the Section 'Introduction'. Systems available on the market consist of up to 100 LED chips and, thus, only offer limited possibilities of adapting the light distribution in a desired way as mentioned in Section 1. The projection of information on the road is not possible with this technology so that it cannot actually be called a pixel light system. It still is a first step toward such a headlamp system and can easily be expanded when implementing an LED array.

2.2 LED arrays

Many LED chips are arranged as a (typically planar) array and projected with one common optical system onto the

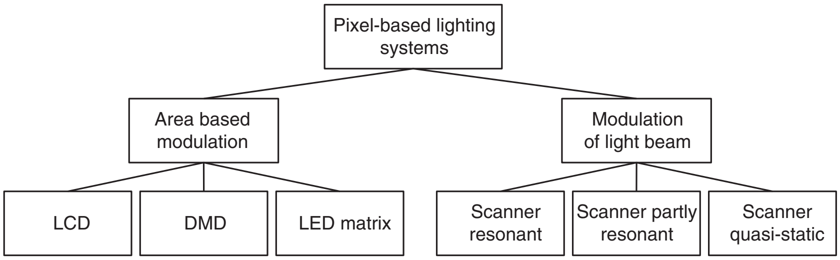

Figure 2: Image generation techniques for vehicle headlamps according to [9].

road. Each LED or small group of LEDs addresses a specific area of the light distribution and can be switched and dimmed individually [10]. A vehicle lighting distribution requires an aspect ratio of 6:1. Therefore, either an accordingly shaped LED array or an anamorphic projection system [11] can be used. The latter widens up the light distribution in horizontal direction, which allows the use of any quadratic or rectangular-shaped LED array. All automotive headlamps generate a high illuminance in the middle of their emission pattern to illuminate the road in a certain distance (the so-called hot spot). Therefore, in one solution, the spacing between the LEDs can be reduced in the middle of the array to generate this high illuminance, or different LED chips can be used.

2.3 DMD

A DMD as area-based light modulator is illuminated and projected onto the road. This technology offers the possibility to generate an adaptive light distribution while simultaneously addressing each single pixel. DMDs consist of many small micro-mirrors, each of them capable of changing between two states. Light directed at the micro-mirror will either be deflected onto the road and, thus, be part of the light distribution or onto an absorber. Dimmed states are realized by a fast change between the on and the off position.

In order to generate a hot spot, the illuminance in the center of the DMD can be increased. Owing to the limited reflectivity of the DMD, thermal losses occur so that the module is heated up. This leads to a limitation in the maximum illuminance on the DMD and, hence, the overall luminous flux of the system. Texas Instruments recently added a DMD certified for automotive applications with WVGA resolution to its products [12]. As DMD arrays typically do not offer an aspect ratio of 6:1 an anamorphic projection system can be used as described in Section 2.2.

2.4 LCD

Instead of a DMD, LCDs can be used to generate the pixel-based light information. Using a DMD, a certain space between light source and DMD is necessary as path for the reflected light. LCD-based systems can be designed smaller as an LED array as illumination source can be placed close to the LCD [13, 14]. On the other hand, the efficiency of an LCD is low in combination with an unpolarized light source. Using the polarized light from laser diodes to illuminate the LCD, the system efficiency can be increased [15].

2.5 Scanning systems

A small micro-mirror with two rotational degrees of freedom is used for the generation of a projection on the road. The light from one or more light sources is deflected by the mirror and, thus, creates an image as desired [16]. When creating an image with only one mirror, very high speed of mirror movement is necessary. This is easier to accomplish with small mirror sizes of about 1 mm^2.

The light beam has to be collimated very precisely as the divergence angle of the beam defines the size of a single pixel on a wall. For projection on the road, the distance between scanning unit and the illuminated point on the road surface has to be considered as well. The small mirror in combination with the claim for a nearly collimated beam narrows down the list of possible light sources as it has to have a very small étendue.

LEDs, even those with a small emission surface, cannot be used efficiently. Owing to the wide emission pattern of an LED and its extended emission surface, it is impossible to collimate great amounts of the light and focus it on the small mirror. Laser diodes are a good alternative for scanning mirror systems. They have a very small emission surface of only a few μm, which is much smaller than the emission surface of an LED, so that the beam can easily be shaped using simple lens setups. This advantage of lasers in combination with the high possible switching speed enables addressing each point in the desired light distribution individually.

As mentioned in Section 1.2, white light can be generated with laser diodes either by mixing the output of different diodes or by using a phosphor conversion element. The first approach offers a great color gamut, while it is easy to generate a colored image. But the exact adjustment of a specific color mixture is challenging (see Section 1.2). Using the second approach, the focused laser spot is moved on a phosphor plate. This plate is projected onto the road, while each position on the plate represents a specific area of the light distribution [17].

There are three approaches when setting up a scanning laser system differing in how the scanning mirror is used:

- Both axes can be operated in resonant mode (Figure 3A). This allows high frame rates but requires a very high switching speed of the laser diodes. The frequencies of both axes should not have a common divisor, which would lower the pixel resolution of the system. Owing to the sinusoidal path and velocity characteristics of the resonant mode, the laser beam is slower at the edges of the illuminated area, generating a higher illuminance there, while it is relatively low in the center. Vehicle headlamps require a different light pattern with the highest amount of light in the middle. Therefore, the use of resonant scanners as vehicle headlamps would require very high intensities of the light source [18]. This system is well suited for the generation of large area symbols as the frame rate is not influenced by the projected information.
- One axis can be driven in resonant mode, while the other is operated quasi-static (Figure 3B). This system is, as the one mentioned before, well suited for the generation of large area symbols. The disadvantage of wasting light at the four edges of the illuminated area is more or less reduced to two edges.
- Both axes can be operated in a quasi-static mode. This approach is the best for the projection of contours. The laser beam follows the outline of the symbol exactly, while corners are smoothened by the addition of tangentially connected curves (Figure 3C). Such systems provide the sharpest contours, outperforming even DMD-based systems due to the lack of aliasing. The laser can be switched on nearly all the time so that the generated image is very bright. But the projection of large area symbols leads to very low frame rates and dark images.

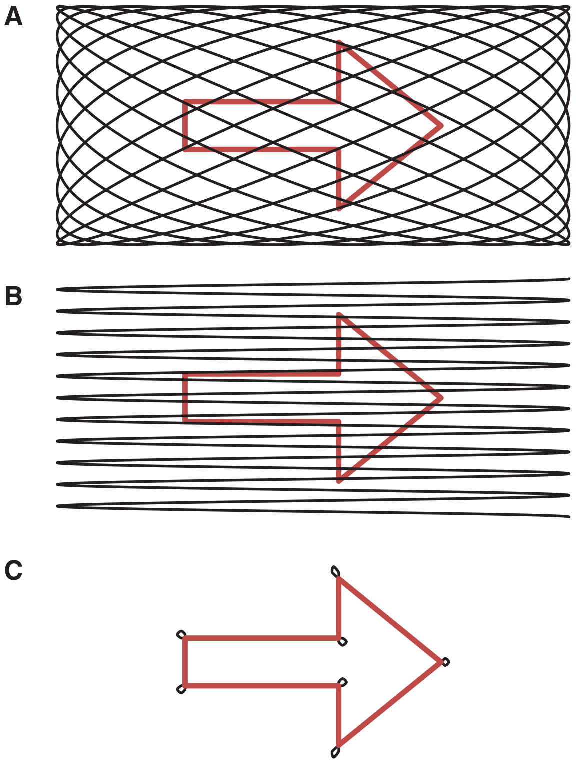

Figure 3: Symbol generation with (A) two resonant axes, (B) one resonant and one direct axis, and (C) both axes direct.

3 Prototype system

3.1 System setup

As analyzed in Section 2, scanning systems offer a broad variety of applications in vehicle lighting (see also Table 1). The system is highly dynamic and adaptable and can realize very high resolutions when using a combination of different direct lasers as light source. Owing to lasers being edge emitters with a very small emission surface (~4 μm^2 in contrast to high power LEDs with ~1 mm^2), the beam can be easily shaped and collimated or focused. This beam can be directed on a small diameter micro-mirror, which opens up the possibility to use higher frequencies for the mirror. In the prototype system we set up, three laser diodes in combination with a MEMS mirror device are used to generate images. The functional structure of the system is shown in Figure 4.

For the system setup, laser diodes with three different peak wavelengths are used: 450 nm blue with a maximum of 1.6 W optical output power, 520 nm green with 150 mW optical output power at maximum, and 638 nm red emitting up to 500 mW optical.

Table 1: Comparison of different adaptive front lighting technologies.

	Scanning system resonant	Scanning system direct	Multiple LEDs with optics	LED array	DMD	LCD
Resolution	+	+	-	o	+	+
Optical efficiency	o	+	+	o	-	-
Simple switching control of light source	-	o	o	o	+	+
Light source with large étendue applicable	-	-	o	o	o	+
Luminous flux of system	-	-	+	o	o	-
System size	+	+	-	+	o	+
Image contrast	o	+	o	o	o	-
Projection of contours	-	+	-	-	o	o
Projection of large area symbols	+	-	-	+	+	+
Color projection	+	+	-	-	o	o

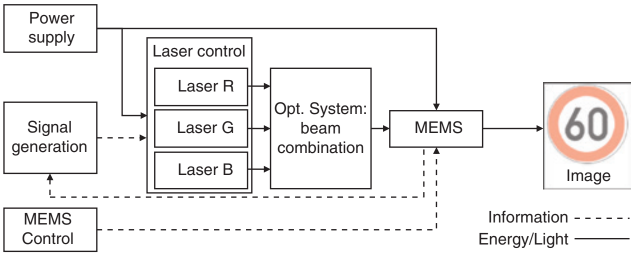

Figure 4: Functional structure of scanning unit.

Table 2: Characteristic values for the diodes [19–21].

Diode color	Red	Green	Blue
Optical output power	0.5 W	0.15 W	1.6 W
Emission wavelength	638±6 nm	520±10 nm	450±10 nm
Beam divergence $\Theta_{\perp,\mathrm{FWHM}}$	36°	23°	23°
Beam divergence $\Theta_{\parallel,\mathrm{FWHM}}$	6°	7°	7°
Polarization	p	s	p

In the chosen setup of a semi-resonant scanning projection system, very high switching frequencies of the diodes' light output are necessary. To achieve this, special driving electronics have been implemented. The electrical drivers open up the possibility to operate the diodes individually at frequencies around 10 MHz each (rise time of 14 ns and fall time of 23 ns). This way, the total system resolution can reach the desired value of at least 128×64 pixels.

In order to make a compromise between high optical output power and a good emission characteristic, the diodes were chosen as presented in Table 2. The angles of the beam divergence still differ and have to be considered in the system layout. Depending on the color output that is desired, the diodes' electrical power also has to be adapted. Owing to the characteristics of the human eye, represented by the V(λ)-curve (daylight vision), the system's total luminous flux for white light is either limited by the green or the red diode, depending on the desired chromaticity coordinates.

An important aspect when using multiple laser sources is superimposition of the different laser beams. To realize this, dichroic mirrors are used. Dichroic mirrors are coated in a way that they transmit a certain range of wavelengths, whereas they are reflective for others. Depending on the emission wavelengths of the diodes used, a suitable coating has to be chosen. Figure 5 shows the optical setup of the system. To combine the beams of all three lasers, two dichroic mirrors are necessary. One mirror transmits red and reflects green light with a cutoff wavelength of 567 nm, and the other is transmitting red and green light while reflecting the blue amount (cutoff at 466 nm).

For each diode, a primary lens is applied close to the emission point. This lens can be used for collimating the beam, which means to make the beam parallel and close to round in its form. In the setup shown here, the primary optic is used for pre-shaping the beam so that, in combination with a second lens, it is focused on the micro-mirror but also widening up afterwards. So with a larger distance from the micro-mirror, the size of the laser spot will increase. As shown in Table 2, the beam divergence is not only differing within the diodes but also depends on the orientation of the diode. For the scanning system, a close to squared spot is preferred. In order to achieve this, a cylindrical lens is added to the system. The lens has a working distance of 100 mm from the micro-mirror, but it is mounted on a rail so that its final position in the setup can be adapted according to the desired spot geometry. As the cylindrical lens is combined with the pre-shaping primary lens, for a change in the spot geometry, all the lenses have to be adapted.

The goal is to create a laser spot of 50×50 mm^2 in spot size at a distance of 10 m from the scanner. In order to achieve this, the beam divergence (half angle) has to be 0.14° illuminating the micro-mirror. As all laser diodes

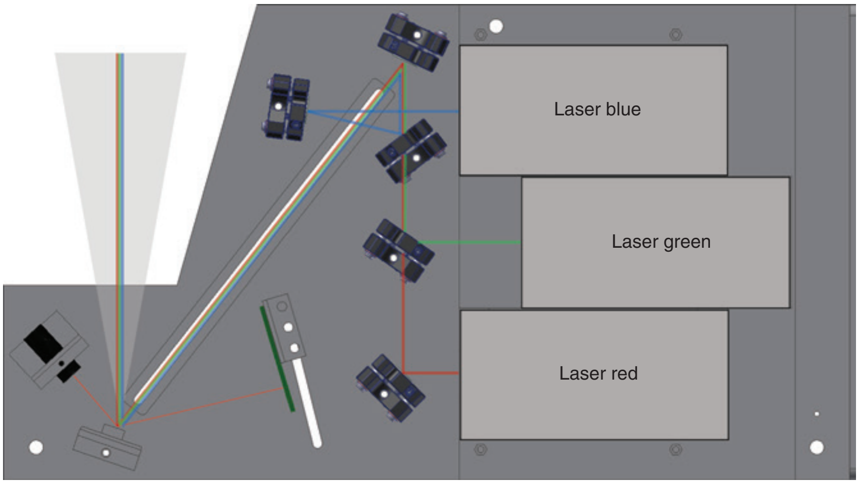

Figure 5: Optical system setup.

have different beam divergences, a combination of lens distance from the diode and length of the optical path has to be realized to achieve the same beam divergence for all three lasers. For the system shown in Figure 5, the actual optical paths from diode to MEMS are 385 mm for red, 324 mm for green, and 368 mm for blue. As the red diode has the largest beam divergence in one axis, higher optical losses in the primary lens have to be accepted. As the green and red diodes both limit the possible total output power for generating white light, their optical paths have to be as simple as possible in order to ensure the highest optical efficiency. As the blue diode offers the highest output power while comparatively little of it is needed for white light, the beam can be deflected by an additional mirror. This mirror adds two further degrees of freedom (DOF) to the system's optical path, which is necessary for laser alignment and superimposition of the beams.

Each mirror shown in Figure 5 can be tilted using two adjusting screws, so that it opens up two degrees of freedom for the beam. Setting up the beam superimposition begins with the adjustment of the red laser. It is aligned with the green laser using one broadband and one dichroic mirror. The broadband mirror is used to overlay the laser spots of green and red on the dichroic mirror. The direction of the green beam is then aligned with the red one using the DOFs of the dichroitic mirror, which does not affect the direction of the red beam. In total, 10 DOFs are available to align the whole system. Eight DOFs are used to overlay the three beams, while further two DOFs are required to direct the aligned beams onto the MEMS. So all 10 DOFs available are necessary for proper alignment of the three laser beams creating one single spot. The resulting spot geometry for the prototype setup is shown in Figure 6.

When emitting direct laser light to the outside, eye safety has to be considered. The setup presented uses a divergent beam that leads to a reduction of radiation intensity with increasing distance from the source. Depending on the divergence angle and the laser power applied, the system is possibly dangerous for eyes in a certain range. As in a scanning system the laser beam is always in motion, the time-averaged intensity of radiation is very low compared to the static beam. Nevertheless, safety measures have to be implemented. The system should only be turned on when the vehicle is moving and has reached a certain speed. One possible solution is to combine the laser activation with the automatic door lock system. In combination with the vehicle camera and its detection capabilities, emergency stop scenarios for unclear situations (pedestrians, bad road conditions, etc.) have to be implemented. As pitching of the vehicle can lead to uncontrolled emission directions, it is suggested to mount the scanning device as high as possible.

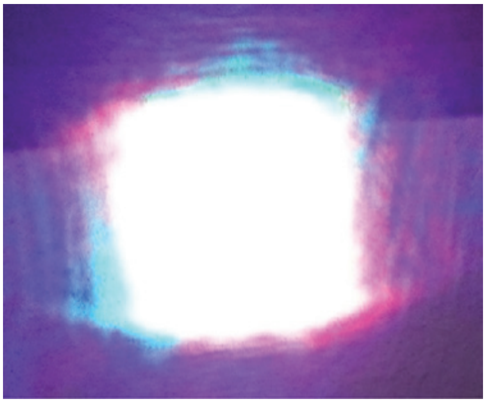

Figure 6: Photo of the laser spot in prototype setup [6].

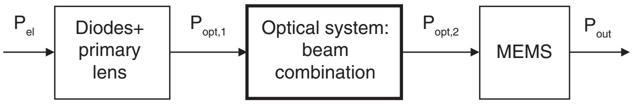

Figure 7: Power and efficiency of the laser scanning unit.

3.2 System parameters and measurement results

The laser scanning system has been set up as described in Section 3.1 allowing a maximum theoretical output power of 2250 mW optical with all diodes at their maximum operating current (see Table 2). By reducing the current of blue and red (as well as green a little bit), a white point is chosen for further efficiency analysis. The measured light output at the micro-mirror for this white consists of 112 mW red, 67 mW green, and 110 mW blue leading to a total of 289 mW optical output power. As the scanning unit is meant to project symbols and images rather than to generate an ECE light distribution, the chromaticity coordinates for this white do not necessarily have to be within the ECE white definition. The operating scanner will adapt the projected color according to the requirements of the displayed image. In order to determine the efficiency of the optical system, the diodes' light output (after primary lens) is measured as well. This leads to the optical power without beam combination and MEMS as shown in Figure 7 ($P_{opt,1}$).

For the setup analyzed, the corresponding output power values of the diodes are 320 mW red, 129 mW green, and 220 mW blue. Comparing P_{out} and $P_{opt,1}$, the efficiency of the optical system including the micro-mirror can be determined for each diode. It is 35% for red, 52% for green, and 50% for the blue diode's beam path. Especially, the red beam loses a lot of its energy in the optical system, which is mainly due to its greater beam divergence at the diode output. A starting point for an improvement of the system's efficiency can be the micro-mirror coating, which in this case was not optimized for the wavelengths used in this setup and, thus, leads to losses of around 20% optical power. The combined optical output for white, thus, has an efficiency of about 43% in the optical system of the presented setup. Nonetheless, the system can be used to project large area symbols on top of a static light distribution and are shown in Figure 8 as also presented in [6].

4 Summary and conclusion

The automotive headlight development currently focuses on very high-resolution lighting systems for fully adaptive light distributions. To achieve this, many different technologies can be used as presented in Section 2 of this article. Which technology is best highly depends on the desired functionality of the product being developed. The system analyzed here is a scanning projection unit based on laser diodes as light source. Its goal is to build a light module for the projection of symbols and images around the vehicle in order to add further functionality to assist the vehicle's driver. The first results prove this concept and show the potential of such a system but also demonstrate challenges that still have to be faced.

A crucial further step in order to make laser scanning units more efficient is the diode development. Laser diodes as the ones used for the presented demonstrator currently have a wall-plug efficiency (optical output to electrical input) of 5–30%, which is way below the efficiency of today's LED systems. Also increasing the system's total optical output power is important in order to make it work not only in total darkness but also during dawn or even at daylight. For vehicle integration, the design space has to be reduced, which can be achieved, for example, by using light guides to separate light generation and image generation (lasers and MEMS). Finally, also eye safety issues have to be regarded as with all light sources supplying a high luminous intensity.

Figure 8: Images from working prototype [6].

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