# Photonics in Germany

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*Optische Technologien in Deutschland*



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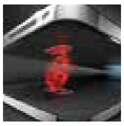



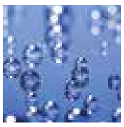



# New High-brightness Laser-based White Light Source for Vehicular Lighting Systems

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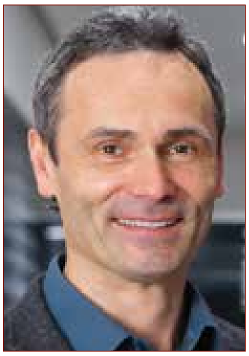

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**ABSTRACT:**
Modern vehicular lighting systems (VLS) are intended to improve safety on the road by providing the adequate visibility to the drivers under different driving conditions from within a compact housing, whilst simultaneously reducing the impact on the environment and meeting the consumer demands in terms of styling and low cost. Using **high-power GaN-based blue laser diodes** that pump a yellow phosphor in a remote position, BMW developed a new **high-brightness white point-like source** having a peak brightness of over 1000 cd/mm², which is 10 times higher than that of high-power white LEDs. By integrating this new light source in a VLS, BMW was able to double the range of the visibility while increasing the VLS's efficiency, keeping its size compact and fulfilling the required light fluxes and intensities.

This illumination method is not restricted to the automotive sector, but it can be generalized to sectors, where efficiency and compactness and/or specific lighting distributions are required.

## 1) SOLID-STATE SOURCES IN AUTOMOTIVE LIGHTING

Errors in the visual perception, namely during night-drives when the vision is limited, were found to be five times higher during night time and cause worldwide 1.25 million fatal accidents a year according to the World Health Organization reviewed in November 2016. Low illumination decreases both the depth of perception and the peripheral vision [1, 2]. Improvement of the night-time visibility using a better illumination pattern of the road contributes to enhance the perception in driving and the control of the vehicle for limited lumen flux respectively energy consumption. The inhomogeneous illumination patterns projected on the road are adequately engineered so as the recognition and the interpretation of the information, such as road marking, distance evaluation, presence person/animals on the road, is facilitated without dazzling the surrounding environment including the on-coming traffic. The international regulations on automotive lighting and signaling define minimum and maximum photometric specifications in each segment of the engineered illumination pattern. Dynamic illumination patterns, such as bending light, glare-free high-beam and marking lighting, are engineered to assist in different driving conditions.

Modern VLSs are intended to improve safety on the road by attempting to providing adequate visibility to the drivers under different driving conditions from within a compact housing, whilst simultaneously reducing the impact on the environment and meeting the consumer demands in terms of styling and low cost. The main objective is to make the driver conditions during night-time similar to that of the daytime ones. Assuming aberration free optics, the forward visibility is expressed in terms of the luminous intensity maximum of an *asymmetrical hot-spot* $\boldsymbol{I}_{hotspot}$ in the illumination patterns as follows [3]:

$$\boldsymbol{I}_{hotspot} = A\, N\, \eta\, L_s \qquad (1)$$

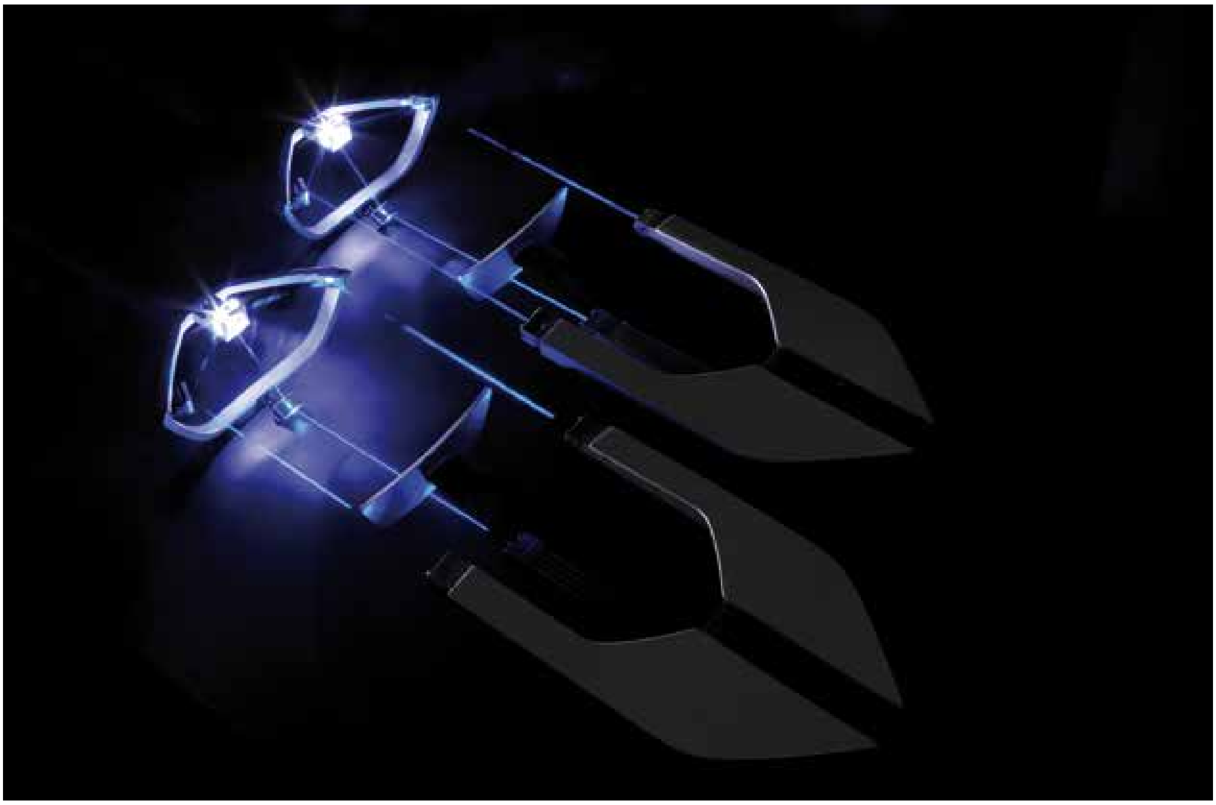
where $L_s$ is the luminance of a lighting module (i. e. central LED chip), $\eta$ is the absorption of the optical system, $A$ is the aperture of a single lighting module and $N$ is the number of contributing modules. One way to enhance the visibility of the drivers in the far-field is to use a large effective aperture $A_{eff} = A{*}N$. The separation in $N$ sub-apertures by using multiple light sources creates the styling freedom, which is visible by the variety of the LED-headlamps existing on the road. However, a large emitting area $A_{eff}$ per headlamp results in a decrease of efficiency for small lit apertures, limited by styling and package requirements. This impacts considerably the geometry and the weight of a headlight. Following this path, a new generation of VLSs based on LED chip array has been developed and brought to the market by different car manufacturers and their suppliers. It is based on a set (84 up to 1024) of individually addressable high-power white LEDs. These systems make use of the instant on/off switching and dimming capabilities of the LEDs to generate a given light illumination pattern. Despite the fact that these light-engines are electronically very demanding and thermally limited, standard static and dynamic illumination patterns could be generated without using mechanical actuators. Already implemented driver assistance lighting functions, such as marking light, could be realized using this technology. However, the photometric performances, namely the range of visibility, are extremely limited, since LED structures suffer from non-thermal drop in efficiency (known as *droop effect*) as the input power density is increased[4]. This loss is translated in terms of heat that has to be dissipated. The cooling systems to remedy this drawback in such light-engines end up to be bulky and heavy.

To achieve new dynamic driver assistance functions with specific illumination patterns a resolution of 0.1° in the far field is needed[5]. Considering a 60mm focal length secondary optics free of aberrations, the minimum size of an LED chip would be 100 µm x 100 µm. Typically, the field of illumination covered by a a headlamp is ±30° x ±10°. To illuminate this field using this technology, an array of 120 000 (600 x 200) LED chips would be needed. This is not realistic if the high-luminance is taken into account.

## 2) LASER DIODE (LD) FOR VLS

Another way to increase the visibility is to develop a new white light source featuring high-luminance $L_s$, as highlighted in the equation above. Such a source would lead to the development of very compact VLS with high-performance and a variety of new lighting functions with high resolution and contrast. This can be achieved by exciting a yellow phosphor in a remote position – also termed *remote phosphor* configuration (see Picture 1) using high-power multimode blue edge-emitting laser diodes (LD)[7], whose respective emitting surface is 5000 up 10000 times smaller than that of the blue chip of a high-power white LED. The radiance of the LD is even 1'000'000 times higher than that of a blue LED.

Unlike LED, the efficiency of LD increases with high input power density. During the last five years, the wall plug efficiency (WPE) i.e. ratio of the radiant power to the electrical one, of blue high-power laser diodes has been considerably improved from 25% to reach 40% at an operating temperature of 25 °C. Thanks to the use of semi-polar/m-polar GaN, thick multi-quantum wells active region and efficient design and manufacturing methods of the LD i.e. chip-on-submount and package, more efficient LDs are to be expected to hit the market in the near future. Yet, VLSs are



**Picture 1:** Experimental setup showing a white light produced by two Cerium(iii)-doped Yttrium Aluminum Garnet (Ce:YAG) phosphor-chips in a remote position that are excited by high-power multimode 450 nm laser diodes (over 1 W).

| LARP 3 (Osram) | µLARP + (Osram) | Gigawhite (Nichia) | Sugar Cube (BMW/SLD) |
|---|---|---|---|
|  |  |  |  |
| • 500cd/mm², 160lm @25°C, CW<br>• Transmissive remote phosphor<br>• Integrated product safety measures<br>• Monolithic configuration<br>• Active cooling<br>• Cost: high | • 500cd/mm², 188lm @25°C, CW<br>• Transmissive remote phosphor<br>• Product safety measures not integrated<br>• Monolithic configuration<br>• Active cooling<br>• Cost: moderate | • 325cd/mm², 258lm @25°C, pulsed<br>• Transmissive remote phosphor<br>• Product safety measures not integrated<br>• Monolithic configuration<br>• Active cooling<br>• Cost: moderate | • over 1000cd/mm², 531lm @25°C, CW<br>• Reflective remote phosphor<br>• Integrated product safety measures<br>• Fiber-based configuration<br>• Passive cooling<br>• Cost: moderate (design to cost) |

**Table 1:** Different laser-based white light engines

located in the vicinity of a combustion engine or electrical batteries, where temperature could reach up to 85 °C. Furthermore, the temperature inside an LED headlight could reach a peak of 110 °C as the junction temperature of an LED is about 150 °C. High-power multimode blue LDs have, however, lower junction temperatures ranging from 90 °C up to a maximum 110 °C. The remote-phosphor configuration (see Picture 1) consists in operating the LD and the phosphor units separately and under different temperature conditions. The LD unit is adequately placed in the headlight, where an efficient convection heat exchange with the cooled air flow generated by the vehicle movement takes place. By operating the LDs at the appropriate operating temperature i.e. under 60 °C and forward current, which lies between the threshold current and the rollover current, the conversion efficiency is maximized namely in a continuous wave driving mode. The robust ceramic phosphor unit together with its secondary optics is placed inside the headlight, where the temperature is high. The usage of a robust optical fiber cable between the two assemblies allows a high flexibility and modularity in the package design. Additionally reflective configuration of the phosphor that enables the local cooling is used to avoid quenching for high luminance. The heat is dissipated through the thickness of the phosphor chip (~ 100 µm), rather than radial dissipation (~ 500 µm), provided the adequate choice of the substrate that takes into account the coefficient of thermal expansion compatibility of the assembly. This reflective configuration permits, furthermore, the recycling of the back-scattered part of the light in the phosphor chip after the reflection at the interface level between the phosphor and the substrate. Under these conditions, the phosphor has to be optimized (composition/doping, grain size, grain distribution and density, thickness) to generate the desired luminance, while fulfilling the color requirement defined by the regulations. As a result, a peak luminance of over 1000 cd/mm², a luminous flux of 530 lm (see Table 1), a conversion efficient of more than 290 lm/Wradiant and a quenching temperature higher than 190 °C were achieved. The FWHM of the emitting spot is 375 µm x 275 µm. This new source is Lambertian and has a broad spectrum. The conception of the LD and phosphor units takes into account the thermo-optical stability to ensure a stable functioning when operated at high temperature.

**Picture 2:** High-Beam Laser-Light Booster in BMW i8

**Picture 3:** Marking lighting to assist drivers to detect not only pedestrians but also animals (e.g. deer) at an adequate distance

### 3) LIABILITY: SAFETY

An important aspect related to the use and integration of high-power laser diode in VLS is the eye and product safety. The light emanating from high-luminance sources could cause eye damages. Therefore, BMW took stringent measures to protect drivers, pedestrians and wildlife in terms of the conception, use and implementation of these new high-luminance point-sources. Similar to Xenon-based headlights, the high-beam laser-light booster is activated according to the cruising speed of the vehicle (e.g. above 40 km/h) after the activation of the main LED-generated high-beam. This intended to avoid any misuse such as having a direct close look at the system in a static position of the vehicle. Being used to generate high-beam lighting and glare-free high-beam functions, the on-coming traffic and traffic ahead is detected to switch it to the low-beam or adaptive driving beam. Furthermore, this new point source is composed of Class 4 high-power blue LDs. As such, its package was constructed to avoid leakages of the high-power coherent blue pumping light. It is also equipped with monitoring photodiodes that detect failure modes of the LDs, phosphor and the optics not only in normal situations but also in crash situations and under degradation-induced effects. The booster will be automatically switched off if a single failure mode is detected.

### 4) RESULTS AND PERSPECTIVES

Such a high-luminance white light source was used not only to extend the range visibility in the BMW i8 vehicle (see Picture 2), but also to enhance the visibility contrast in the BMW 7 series. The maximum visibility range tolerated by the European ECE regulations is about 600 m, which corresponds to an illuminance of 344 lx at 25 m. In fact, we used LED to generate a broad illumination pattern of 64 lx illuminance and the LD-based quasi-collimated white light to generate a spot in the far-field of 290 lx illuminance. This performance has to be achieved from within a compact package (30 mm aperture of the optics) and be stable in the defined operating temperature range.

The development of new laser-based lighting functions, such as driver-assistance dynamic lighting functions shown in Picture 3 require high-luminance light sources and high resolution in the far field. MEMS-based scanning mirrors are extremely compact with high scan frequencies (kHz) and could be robust enough when integrated in the appropriate package. The main challenge ahead is to find out the appropriate configuration and optimal driving method to use the high-power (higher than 4 W) radiating beam(s) from a laser diode in combination with the MEMS-based scanning mirrors for the free patterned illumination purposes, namely in the automotive sector. An alternative to the laser scanning technologies could be the combination of optical phase modulation technologies and laser diodes. Their ability to accurately control the phase of a beam would enable free patterning of light distributions in the automotive lighting sector. In this case, coded patterns would be programmed to create dynamic light distributions without the need of any high scanning frequencies.

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