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Review Article

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System efficiency of laser-based white light

Abstract: For many lighting applications, light-emitting diodes (LEDs) are replacing traditional light sources providing the possibility for smart and efficient systems as well as a reduction in the product weight. A next step in this development is the integration of laser-based light sources to increase luminance and to further scale down the optics possibly leading to a reduction of necessary resources. This article reviews the possibilities and challenges arising from the use of laser diodes especially compared to current high-power LED systems in terms of efficiency, color-rendering properties, and thermal management.

Keywords: laser diodes; LED; phosphors; solid state lighting; system efficiency.

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1 Introduction

Bright white light-emitting diodes (LEDs) become more and more part of lighting applications such as general lights for illumination. They are also changing the traditional automotive headlamp structure, which is based on halogen (tungsten) and HID lamps.

Especially regarding electromobility concepts, the usage of efficient light sources becomes important. So, conventional halogen headlamps are replaced by LED systems. They do not only save electrical energy but also offer new possibilities for the optical design because many semiconductor chips can be combined to one headlamp. Along with this development, reliability issues regarding multichip systems have to be taken into consideration as well.

Using laser diodes is a further step in this development. Their very small light-emitting surface offers great possibilities to create sharp and exact light distributions. Owing to the reduced amount of stray light, the ratio between emitted light flux and produced illuminance can be increased. This offers the possibility to develop small optical systems based on the principles of geometrical optics.

At the Institute of Product Development, we set up a demonstrator using laser-activated remote phosphor as a light source for an additional high beam module supporting the traditional high beam and, thus, extending its range. This shows the challenges and opportunities of the lately rising laser diode technology [1].

2 Semiconductors as a light source

LEDs as well as laser diodes are semiconductor light sources. The generation of light is done by electrical stimulation of a doped semiconductor material, e.g., InGaN, which emits photons of a specific energy amount and, thus, of a specific wavelength. Depending on the semiconductor material, different emitted wavelengths can be achieved.

The light emitted from a conventional LED has a typical spectrum with a full width at half maximum (FWHM) in the range of 40 nm–70 nm [2]. In consequence, visible LEDs show a highly saturated color. Laser diodes emit a much narrower spectrum. For a high-power multimode blue diode, it is about 1.5 nm [3].

While the light output of LEDs can be controlled either by adapting the diode's forward current or by using pulse-width modulation (PWM) at nominal current, only the latter is recommended for laser diodes. Owing to the lasing threshold, the wall plug efficiency (WPE, see Section 3.1) of the diode would otherwise be reduced (Figure 1). But of course, the efficiency of the control electronics at different operating conditions (continuous or pulsed) has to be taken into account as well.

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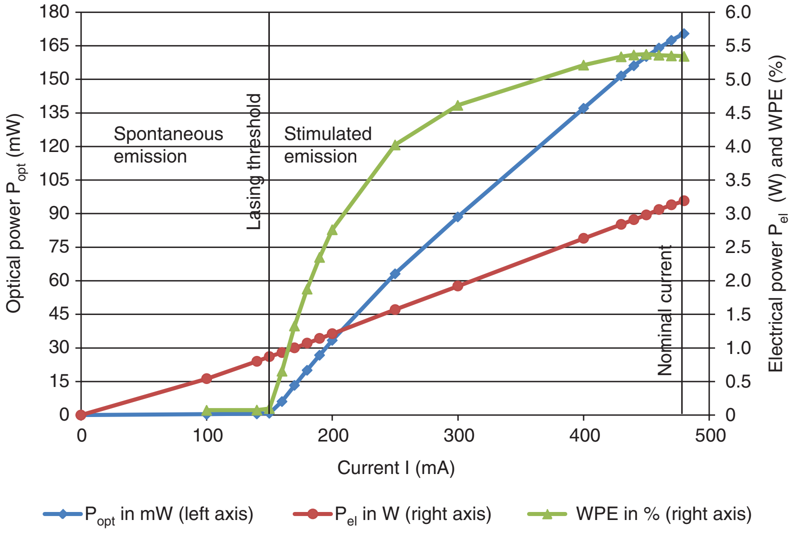

Figure 1 Optical output power and WPE vs. driving current characteristic of a green laser diode at fixed case temperature.

3 System efficiency

3.1 Luminous efficacy and maximum theoretical efficiency

Regarding an illumination system consisting of a diode driver, diode with conversion layer, and an optical system, the efficiency can be calculated as depicted in Figure 2. The diode driver generates a constant or PWM modulated current to operate the semiconductor light source. Its efficiency η_{driv} is typically 80–95%.

The efficacy of the light source, itself, is called WPE, which is the ratio of electrical input power P_{in} to optical output power.

The WPE depends on the internal quantum efficiency of the semiconductor chip and its extraction efficiency [2]. While the WPE of high-power blue laser diodes available on the market is around 25% [4], Peters et al. reported an electrical-to-optical efficacy of a NIR laser diode of 76% [5].

If the light source works with a conversion layer, its efficiency η_{conv} also defines the system efficiency. This conversion efficiency strongly depends on the output

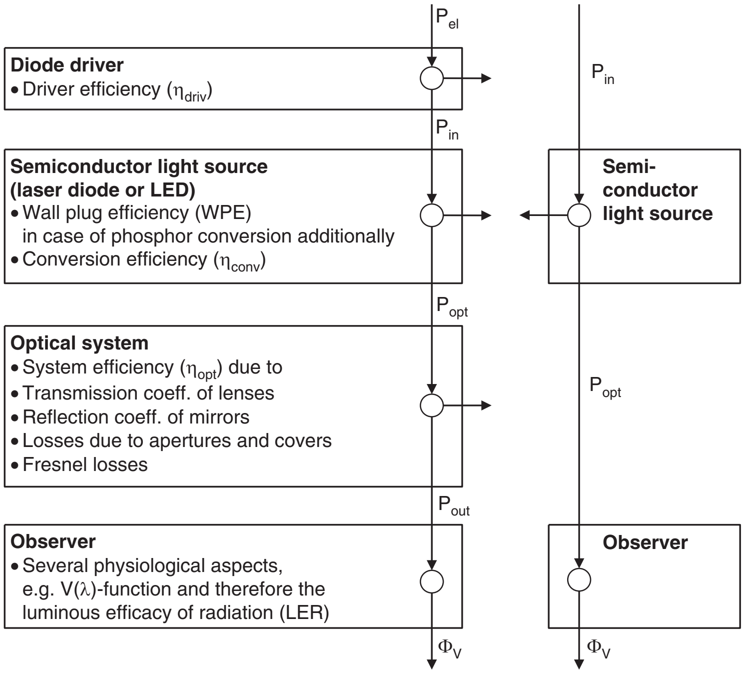

Figure 2 Efficacy of an illumination system (left) and of a semiconductor light source (right).

wavelength of the semiconductor chip and the operating temperature.

Evaluating an optical system, its wavelength-depending efficiency η_{sys} has to be considered as well. For example, the reflection coefficient of a well-done aluminum coating is 91.5% at 550 nm [6]. Each uncoated transmitting surface effects Fresnel losses of about 4% depending on the material. If the incident angle of the light is a lot smaller than 90°, this value is increased significantly. Hence, a simple glass lens has a transmission efficiency of $0.96^2 \cong 92\%$. This value can be increased by using an antireflective coating.

The amount of light detected by an observer depends on many physiological aspects. This is defined as luminous flux Φ_V. The relation between this value and the optical output power of the system is given by the luminous efficacy of radiation (LER). The maximum theoretical LER for white light depends on the color temperature and the required color-rendering index (R_a or CRI). Independent of the R_a value, the most efficient light sources have color temperatures between 2000 K and 3000 K. The only exception for this is a value R_a=100, where a color temperature of 5000–5500 K is required for a high LER. The efficiency decreases significantly for R_a>95. For R_a=100, a continuous spectrum is required, and this lowers the performance significantly [7]. The overall illumination efficiency can be calculated by multiplying all these subsystem efficiencies. Defining the overall luminous efficacy LE of a light source, the diode driver as well as the optical system is not regarded as $\mathrm{LE}=\mathrm{WPE}\cdot\eta_{conv}\cdot\mathrm{LER}$. But nevertheless, for a well-founded examination, these factors also have to be evaluated (Figure 2).

3.2 Efficiency of high-power LEDs and thermal resistances

High-power LEDs are integrated into a broad variety of applications such as medical lamps, spotlights, as well as general lighting. Especially regarding the automotive sector, multichip LEDs with a luminous flux of more than 1000 lm are used to achieve the illumination necessary for a high beam. When handling high-power light sources, it is important to consider the system efficiency as the energy not converted has to be dissipated as heat. This creates important challenges to the heat flow resistance of the LED package, housing, etc.

Some LEDs specified and used for automotive applications are shown in Table 1 as an example with their typical luminous efficacy, maximum thermal resistance of the chip, and typical luminous flux. The LED series are OSRAM OSTAR, OSRAM OSLON Black Flat, and Philips LUXEON Rebel. The luminous efficacy (LE) is a calculated value with information taken from the LEDs' datasheets at a case temperature of T_{case}=25°C:

$$\mathrm{LE}=\frac{\Phi_V}{U_F\cdot I_F}$$

with Φ_V=typical luminous flux, U_F=forward voltage, I_F=nominal current for luminous flux.

For comparison, one example of a laser-based white light source is also given. The laser diode used is OSRAM PL-TB450 with a nominal optical output power of 1.4 W at ~450 nm. The laser beam is collimated onto a sample plate of ChromaLit™ from Intematix® (CL 750 XT). The emitted light is measured with an integrating sphere. The luminous flux of this remote phosphor setup depends largely on the laser spot size, the thickness of the phosphor coating, the surface it is coated upon, and on the mixture of the phosphor.

The luminous efficacy of today's high-power LEDs can generally be assumed to be about 110 lm/W. In contrast to high-power LEDs midpower ones have a lower luminous intensity and luminous flux. Hence, the thermal management is easier than with high-power LEDs, and the luminous efficacy is increased.

Table 1 Comparison of white diodes for automotive applications (values from data sheets, except for luminous flux of no. 7) [3, 8–12], according to [13].

No.	Diode	Luminous efficacy (lm/W), T_{case}=25°C	Max thermal resistance R_{jc}	Luminous flux T_{case}=25°C
1	OSLON Black Flat KW H2L531.TE	98.5	1.9 K/W	500…800 lm at 1000 mA
2	OSLON Black Flat LUW H9QP	81.0 … 127.0	7.5 K/W	180…280 lm at 700 mA
3	OSRAM OSTAR LE UW U1A3 01	63.0 … 112.0	3.6 K/W	630…1120 lm at 1000 mA
4	OSRAM OSTAR LE UW U1A5 01	88.2	2.5 K/W	1120…1800 lm at 1000 mA
5	PHILIPS LXMA-PW01-0110	97.4	10 K/W	199 lm at 700 mA
6	PHILIPS LXMA-PW01-0130	114.0	10 K/W	233 lm at 700 mA
7	OSRAM PL TB450 (experimental phosphor setup)	42.0	18 K/W	239 lm at 1200 mA

The luminous efficacy of LEDs could still be increased due to new developments as the physical limitations of the phosphor conversion and the light generation in the diode chip are not reached yet. Laboratory LEDs already reach 276 lm/W [14].

3.3 Laser diode-based white light sources

Like LEDs, laser diodes alone are not suitable for most lighting tasks due to their nearly monochromatic emission and, therefore, low color-rendering indices. Generating white light with laser diodes is possible by using a blue or UV-diode in combination with a phosphor layer (A and B in Figure 3). This layer absorbs light of short wavelengths and emits visible light with increased wavelength. Using a blue diode (A) one part of the light is converted to yellow. In combination with blue light from the laser diode, white light is generated. The blue light is strayed by the phosphor, while its wavelength stays unaffected. Depending on the phosphor blend used, different efficiencies and color-rendering indices are achieved. Alternatively, a blend of phosphors is used to convert near-UV light to visible light (B). The advantage of this technique is that unconverted laser light can be blocked by a dichroic or absorbing filter to create a safe light source [15].

As a third possibility, at least two laser diodes of different wavelengths are combined to generate white light (C). Dichroic mirrors as well as a light guide combiner may be used for this purpose. A good color-rendering index of a system consisting of four laser diodes is possible, while the reduction of speckles is an important challenge when developing a light source for illumination [16].

3.4 Light sources based on blue laser diodes and phosphor conversion

In Section 3.3, three general approaches to generate white light using laser diodes have been presented. A white light source based on a blue laser diode in combination with a phosphor in remote position prevents the efficacy-reducing reabsorption, which is typical for phosphor-converted white LEDs [17]. In addition, the two heat-source semiconductor and conversion layer are separated [18]. Different phosphor mixtures have been analyzed regarding their output luminous flux and color-rendering index (CRI, R_a). The results of the measurements are shown in Table 2.

The characteristic values for the white laser light shown in Table 2 are measured using a blue laser diode (OSRAM PL-TB450B with 450 nm [20]) at T_{case}=25°C except for the values of CL-750-LR and CL-840-LR where T_{case}=15°C as in [4]. The laser diode is placed outside an integrating sphere, and the beam is focused on the phosphor samples in the center of the sphere (Figure 4). This allows the measurement of the values including the spectral distribution of the generated light.

The measurement is done in a highly reflective integrating sphere, which reduces the influence of the light direction characteristic of the phosphor sample. The measurement system is calibrated with a tungsten calibration bulb, which leads to a high measurement uncertainty for wavelength below 400 nm. As the activating laser light source emits at about 450 nm, this effect is negligible. Between 400 and 450 nm, the relative error is 8.2%; between 450 and 800 nm, it drops down to 3.4–3.5%.

An important goal in light source development is always to increase both efficacy and CRI. The chosen setup with a remote phosphor allows the use of multiple and even different diodes to be focused on the same spot possibly resulting in a much higher CRI, while keeping a high luminous efficacy as Mirhosseini et al. suggest [21].

The photometric properties of a phosphor highly depend on the mixture of the elements in combination with reflecting particles. Some of the phosphors analyzed are development samples provided by Intematix® and could be adapted to special requirements if necessary; they were not specifically designed for application in a laser-activated remote phosphor system. The output

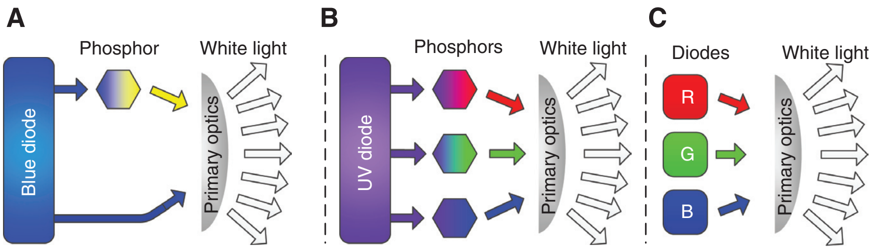

Figure 3 Scheme of laser-based white light sources: (A) mixing direct blue light and phosphor-converted light; (B) converting total output of diode; (C) mixing of different diodes (RGB-laser) [13].

Table 2 Luminous flux and CRI for several phosphors/light sources [19].

Phosphor	Luminous flux	Color temperature	Color rendering index (R_a)	Amount of red light
EY4156	160 lm	7180 K	55	0.05
EY4453	205 lm	5410 K	56	0.07
NYAG4156-L	304 lm	5750 K	59	0.06
NYAG4355-L	226 lm	5300 K	60	0.07
CL-750-LR	343 lm	6350 K	70	0.09
CL-840-LR	325 lm	4630 K	75	0.11
LED Osram Duris E5	104 lm	5610 K	82	0.13
Xenon HID	–	4120 K	65	0.08

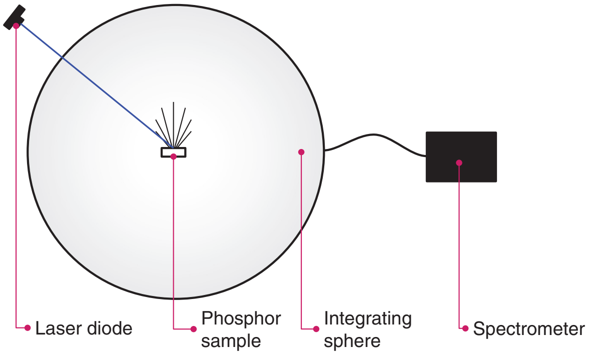

Figure 4 Experimental setup for luminous flux measurement.

luminous flux can vary a lot when the setup is slightly changed. For this reason, all phosphor measurements in Table 2 are performed in one session. Only the phosphors were exchanged. The LED Osram Duris E5 is not operated, but instead, the covering phosphor layer is also activated by the remotely placed laser diode. Only the Xenon HID lamp from a vehicle headlamp uses a different setup. For this reason, no luminous flux is given.

The ChromaLit™ phosphors from Intematix® were already applied as a thin layer to a glass plate (CL-750-LR and CL-840-LR). They are intended to be used as a transmissive phosphor being illuminated from the back by a blue LED. The plate then emits white light in every direction. The other sample phosphors (EY and NYAG) are applied to a metal surface. This way, the light is only emitted from one side. Using a metal plate also allows better heat dissipation from the phosphor. This way, the laser beam can be focused to a small spot on the phosphor. This leads to a very small light-emitting area and, thus, allows the optical system to be more efficient. In order to achieve an even higher-energy density on the phosphor, ceramic materials can be used [22].

Additionally to color rendering especially for automotive applications, the color coordinates have to be within a target area defined in the regulations of the UNECE [23]. The target area as well as the chromaticity coordinates of the phosphors are given in Figure 5. The amount of the luminous flux in the region of 610–780 nm (red light) has to be at least 5% for LED headlamps [24]. Owing to the phosphor conversion, this value is typically low for cold white light sources. Although defined for LED headlamps, this regulation should be taken into account for laser-based headlamps as well.

Some of the phosphors meeting the ECE white target area (Figure 5) are further investigated regarding their behavior when the diode's parameters are changed. Figure 6 shows the results of measurements where the diode current as well as the case temperature have been varied. The case temperature is controlled within the range from 25°C to 50°C using a Peltier element; the diode current is set from 400 mA to 1200 mA. Both changes result in a difference in the optical output power of the diode and, thus, different chromaticity coordinates. When using diodes in lighting applications, they are always subject to environmental conditions, which lead to these shifts in color temperature (and coordinates) as shown in Figure 6.

The blue laser diode used for our experiments generates a maximum of ~1.5 W cw optical output power (including losses due to collimation optics) while consuming 5.68 W of electrical input power, that is ~26.4% WPE at a case temperature of 25°C. The spectra of some combinations of the laser diode with different phosphors are given in Figure 7.

4 Lifetime calculation

While the lifetime of LED chips is within the range of 20 000–50 000 h at junction temperatures T_j=25°C, the lifetime of laser diodes is much lower. Thereby, the semiconductor lifetime strongly depends on the junction temperature. Owing to the high internal thermal resistances R_{jc} of today's laser diodes, the environment temperature

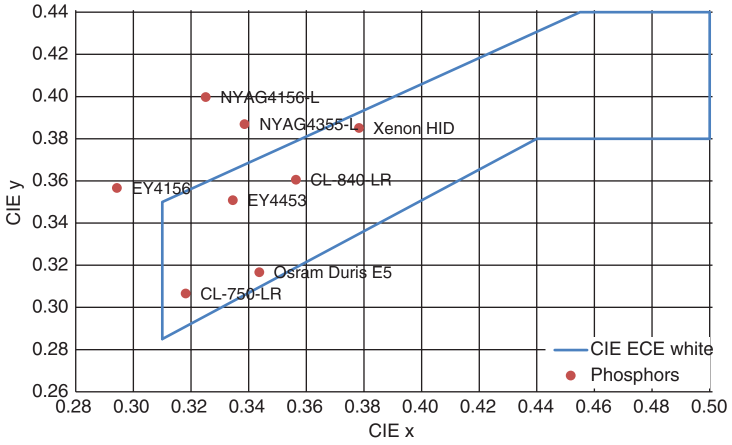

Figure 5 Color coordinates of the phosphors analyzed in comparison to Xenon HID [19].

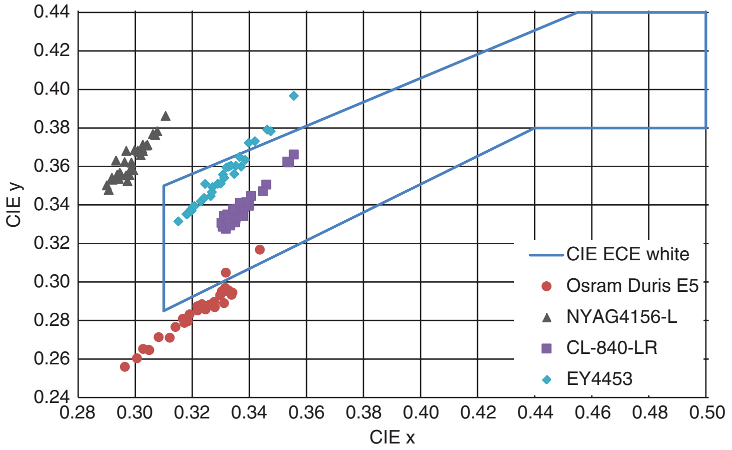

Figure 6 Chromaticity coordinates of selected phosphors at varied diode states [19].

has to be low to keep the junction temperature below the desired value (typically ~150°C [13]). Only some years ago, LED development had to face the same challenges, which have now been mostly solved. A typical value for today's high power LEDs is around R_{jc}=2 K/W, while high-power blue laser diodes achieve R_{jc}=15 K/W [20] (see also Table 1). Improvements take place, and recently, the thermal resistance R_{jc} of Osram's high-power multimode blue laser diode could be reduced from 18 K/W to 15 K/W.

Based on the Arrhenius' equation, the temperature-dependent lifetime of semiconductor components can be calculated. This approach can also be used to approximate the lifetime of LEDs [25]. Transferring this approach to laser diodes, their lifetime can be calculated to

$$L_n = L_{ref} \cdot e^{\left(\frac{E_a}{k_B}\left(\frac{1}{T_n} - \frac{1}{T_{ref}}\right)\right)}$$

with: E_a: activation energy, k_B: Boltzmann constant, T_{ref}: reference temperature, L_{ref}: measured lifetime at temperature T_{ref} [26].

The values for L_{ref} and T_{ref} can be taken from the manufacturers' data sheets. Owing to the lack of reliable values for laser diodes, the activation energy has been calculated using data sheets of LEDs to E_a=0.477 eV [13]. Thus, a lifetime estimation of the laser diode is possible. Regarding a car's application, its lifetime has to reach 1000 h. With a fixed resistance R_{jc}, this defines the maximum temperature of the diodes case T_c (Figure 8). If the case temperature is fixed, it defines the maximum thermal resistance R_{jc}, which a laser diode chip is allowed to have.

Additionally, the efficiency of a laser diode decreases with rising operating temperature. Regarding a phosphor-based illuminating system, its efficacy will decrease if the temperature rises. To maintain a constant luminous flux, the operating current of the laser diode has to be increased, which produces additional thermal losses and, thus, leads to an increased junction temperature T_j. Also, the color temperature of the system will change (see Figure 6).

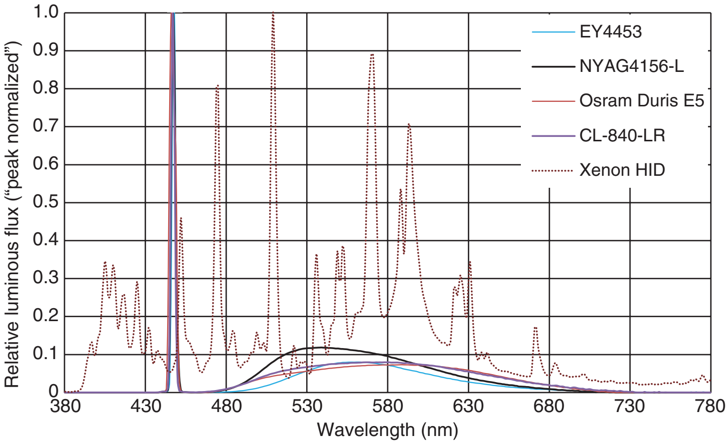

Figure 7 Relative spectral emission of phosphor-converted laser light compared with Xenon-HID according to [19].

Nevertheless, to calculate the lifetime of an illuminating system, the reliability of the electronic driver has also to be taken into account.

5 Summary and conclusion

Laser-based light sources show great potential in increasing energy efficiency. Compared to LEDs, they are still in early stages of development with many options to achieve enhancements. The presented laser-based white light source with a reflective phosphor leads to a maximum total system efficiency $\eta=\Phi_V/P_{el}$=53.5 lm/W. Higher values can be achieved by increasing the WPE of the laser diode or the LER of the phosphor-based white light generation. Reducing the case temperature of the diode leads to higher system efficiencies but is not useful for high-power applications.

The results of the experiments mentioned before show that laser diodes can be seen as an alternative to commonly used LED systems especially when a small optical system is necessary, or the beam-shaping possibilities of a laser light source have to be used. Thereby, smaller optical systems reduce the amount of material needed to build the product and reduce its weight. This may have other advantages like the reduction of fuel consumption for vehicles using lighter optics. The lifetime of today's LEDs outperforms conventional light sources easily. Laser diodes may perform similarly well in the future. This expected extension of diodes' lifetime will also reduce the consumption of resources as the light sources have to be replaced less often.

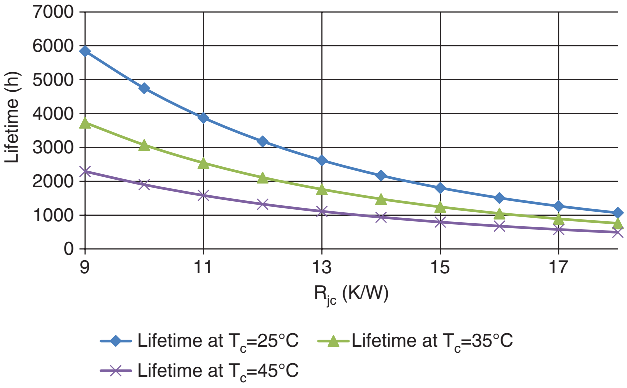

Figure 8 Simulation results for lifetime during R_{jc} at 25°C, 35°C, and 45°C for a specific laser diode [13].

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