Research Article

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Enhancing the luminance of converted green LEDs in LED projectors

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Abstract: High-power light-emitting diodes have successfully found their way into projection applications. Owing to their long lifetime, small size, and easy electrical drive, they are getting more and more attractive for use in various kinds of projectors. The challenge to achieve higher brightness levels lies in the étendue limitation, which is determined mainly by the size of the microdisplay inside the projection system. In this paper, a new approach is presented to increase the output flux of LED-based projectors by enhancing the luminance of converted green LEDs.

Keywords: light-emitting diode; light engine; microdisplay; phosphor; projection.

1 Introduction

The quantity of commercially available LED projectors has increased over the last years, and the number will likely continue on rising [1]. The advantages of high-power LEDs, such as a long lifetime, saturated colors, and low power consumption, have led them into different kinds of projection systems, e.g. pico projectors, home-cinema projectors, and professional control room applications. However, the maximum brightness of LED projectors is limited due to the system étendue. Because of that physical law, it is not possible to increase the flux by simply enlarging the light-emitting area while keeping the size of the imager device constant. One of today's consumer LED projectors with the highest luminous flux – based on the values stated by the manufacturers – is supposed to provide 1400 ANSI lumen [2], while measurements only showed values in the range of 500 ANSI lumen.

An LED projector typically has three LEDs inside, one for every primary color (red, green, and blue). In non-professional applications, commonly one imager device, e.g. a digital micromirror device (DMD) or a liquid-crystal-on-silicon (LCoS) display, is used while the LEDs are driven sequentially. Figure 1 shows schematically one possible topology of an illumination unit of an LED projector. The light emitted by the LEDs is collected and collimated by a suitable lens system and then combined into a common optical path by expedient dichroic beam combiners. The light is then guided toward the projection unit where it is homogenized, used to illuminate the imager device, and finally directed to the screen by the projection lens [3]. White light is generated by operating the colors sequentially with different duty cycles according to the target white point.

Therefore, the projector brightness – which is typically measured according to IEC 61947-1:2002 [4] at a certain white point – can be positively affected by enhancing the luminous flux of the light sources. Figure 2 shows the effect on the relative white luminous output flux if one of the channels is enhanced by a channel enhancement factor (CEF). The duty cycles were modified for every value to hit the target white point according to Rec. 709 (D65, 6500K, $x = 0.3127$, $y = 0.329$). The sum of the duty cycles of the three channels was always 100%. Hence, color overlap was not taken into account. The filter characteristics of the dichroic mirrors typically used in the projection system with cutoff wavelengths at 490 nm and 600 nm have been considered in the calculation.

Measurement results of one set of high-power LEDs for projection applications with an emission area of 8.3 mm^2 and a respective étendue of 26.1 mm^2 sr acted as the calculation base. Table 1 shows the luminous flux and the color coordinates according to CIE 1931 of the three LEDs, which were measured under application-related conditions. The blue and the green LED were driven at a forward current of 32 A and a heatsink temperature of 60°C. The red LED was driven at 24 A and at 40°C heatsink temperature. For

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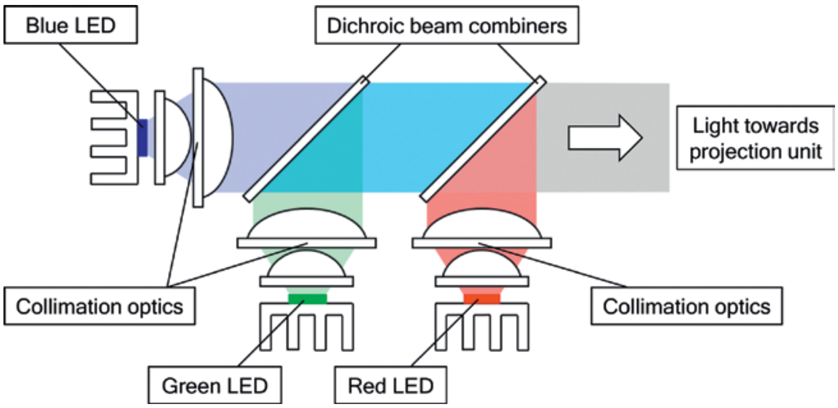

Figure 1: Possible topology of an illumination unit of an LED projector.

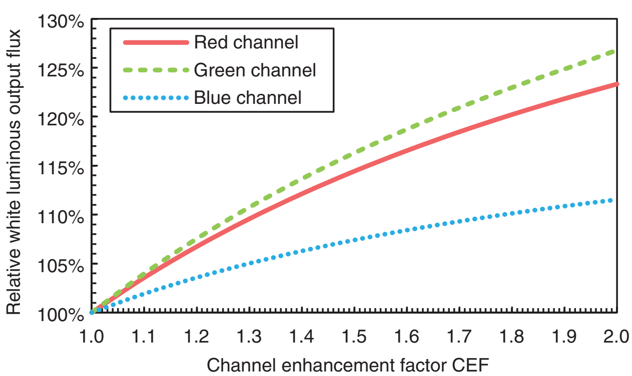

Figure 2: The relative white luminous flux as a function of the channel enhancement factor CEF for the red, green, and blue channels.

Table 1: Measurement results of one set (red, green, blue) of high power LEDs for projection applications.

	Red channel	Green channel	Blue channel
Peak luminous flux	2122 lm	9071 lm	1030 lm
CIE x	0.685	0.327	0.146
CIE y	0.314	0.532	0.038

all devices, the driving frequency was 1000 Hz with a duty cycle of 25%. The peak fluxes are derived by dividing the measured flux by the duty cycle.

An enhancement in one channel results at the same white point in a lower duty cycle for this channel while the on-time of the other two primaries is increased. Figure 2 shows clearly that boosting the green channel has the biggest effect on the white output flux. Doubling the luminous flux of the green LED leads to a gain in the white output flux of about 26%. Therefore, the green channel is the most interesting to be further investigated.

There are already a number of approaches available, which address the green channel of LED projectors. The introduction of optically excited phosphor materials emitting green light enabled several new technologies. Converted green (CG) LEDs – blue LEDs with a green phosphor converter placed on top of the die – are capable of emitting about 75% more luminous flux at the same étendue compared to direct emitting InGaN-based LEDs [5]. CG devices have a wider spectral distribution (FWHM ~ 100 nm) compared to direct InGaN (FWHM ~ 33 nm), but due to the use of wavelength-dependent dichroic filters in the system, this is not an issue in projection applications.

One recent study makes use of a ceramic phosphor rod, which is optically pumped by many blue LEDs positioned at the sidewalls. The light is converted inside the rod and guided toward the outcoupling area. This concept offers two major benefits in projection applications: scalability and a degree of freedom in étendue. The output flux can be scaled by varying the rod length and the number of blue LEDs. The cross-sectional area can be adapted to match the étendue requirements of the imager device. Nevertheless, those advantages are accompanied by some disadvantages, e.g. a larger system size due to the rod length and the needed cooling system [6].

In the scope of this study, a new concept is presented that helps to enhance the luminous flux of converter-based LEDs without increasing the étendue. The basic idea is presented, the potential enhancement factor is determined, and an experimental setup is demonstrated to evaluate the concept. After presenting and discussing the measurement results, a proposal was made to apply the described concept to a common projector illumination unit.

2 Concept

2.1 Basic idea

Conversion-based LEDs used for the green channel of projectors comprise an LED chip emitting blue light and a ceramic converter platelet of the same size, which is located on top of the chip. The platelet consists of a ceramic phosphor material, e.g. cerium-doped rare earth garnet, which has its absorption maxima in the spectral range between 440 nm and 470 nm [5]. This material is able to convert the light emitted by the blue LED into a longer wavelength range with an emission maximum at about 520 nm.

The conversion process is accompanied by different loss processes. A part of the excitation flux is converted to heat due to Stokes shift and the limited quantum efficiency of the material. The thermal load leads to an increase in the platelet temperature, which induces additional thermal quenching, which influences the conversion efficiency negatively [5]. However, the devices outperform direct green emitters in terms of efficacy and total emitted luminous flux. Furthermore, because a saturation of the conversion cannot be observed, it is expected that the excitation limit of the converter is not yet reached and still has a lot of potential. Thus, the excitation radiation has to be enhanced in order to increase the luminous flux emitted by the converter. At the present time, blue high-power LEDs are at their current density limit of approximately 4 A/mm^2 [7], which is set by the manufacturer to ensure the specified lifetime specifications. Hence, new approaches have to be developed to further enhance the pumping power.

The basic idea of the concept presented in the following, is to excite the phosphor converter of a CG LED additionally from the top side with a second light source emitting blue light of a suitable spectrum. One recently published approach already suggested the use of a blue laser array for that purpose [8]. In the present investigation, the extra blue light is emitted by an LED and directed onto the phosphor by two separate parts of an optical system. The first part is used to collect and collimate the light of the extra blue LED; the second one focuses the light onto the converter layer. The second optics is further used to collect and collimate the green light emitted by the converter. A dichroic mirror is used to separate the green output light (wavelengths >490 nm) from the blue pumping light (wavelengths <490 nm) by reflecting one and transmitting the other wavelengths. The concept idea is graphically shown in Figure 3. Depending on the mirror properties (long pass or short pass characteristics), either topology a) or b) may be realizable.

The shown concept is independent of the used chip size and may also be applicable for multi-chip LED arrays comprising a light converter like the OSTAR Projection Power family from OSRAM Opto Semiconductors.

2.2 Potential enhancement

Assuming no losses in the system, an enhancement factor of two is expected, but due to losses along the optical path, the factor is lowered. The part of the optical path that is relevant for the calculation of the enhancement factor begins at the extra blue LED and ends inside the converter layer. The light is converted nearly completely inside the layer and emitted isotropically [6]. Therefore, the direction of the exciting flux only has a minor influence on the emission characteristics. For the calculation of the relative enhancement, it is assumed that the additional blue LED

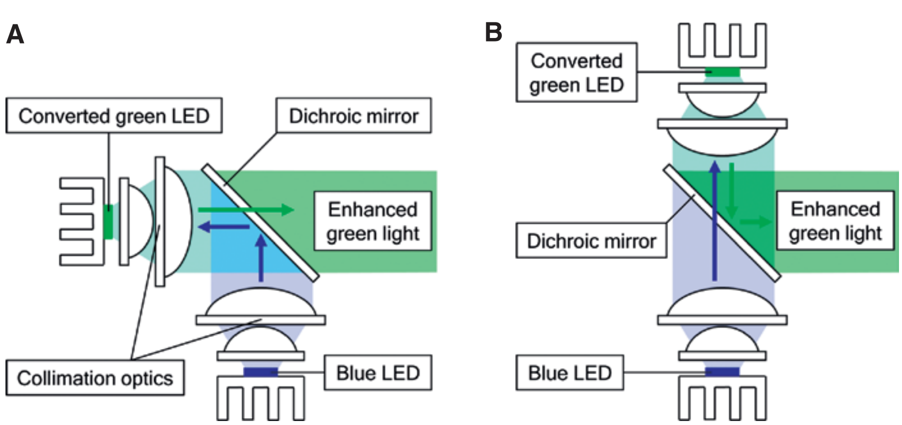

Figure 3: Concept topology A with a long pass and B with a short pass dichroic mirror.

has the same thermal and optical properties as the blue LED located below the converter layer.

The flux that can be used additionally to excite the phosphor depends primarily on the collection angle of the optics. The bigger the collection angle, the higher is the collected flux. The relation between the collected flux Φ_c and the half collection angle θ_c can be expressed for a Lambertian emitter – an LED may be simplified as one – as

$$\Phi_c(\theta_c) = \Phi_{hs} \sin^2(\theta_c)$$

where Φ_{hs} represents the whole flux emitted into the half sphere beyond the emitting surface.

As the second part of the optics is also used to collect the light emitted by the converter, the collection angles should be matched to each other. Owing to étendue conservation, it is not advisable to use a bigger collection angle for the extra blue LED because the light cannot be concentrated onto the converter. For the calculation, it is assumed that two pairs of lenses are used to collimate and concentrate the light. Commonly, the lenses used for that purpose in projectors comprise an antireflective coating; therefore, each of the eight interfaces is expected to cause a loss due to its reflectance of approximately 1.5% [3].

A dichroic mirror matched to an angle of incidence of 45° and the suitable wavelength may comprise a reflectance (topology A) or transmittance (topology B) of 98% in the wavelength range between 420 nm and 480 nm for light having a low divergence angle. Additionally, the divergence angle of about ±5° at the output of the first lens pair and the distance between both pairs of lenses leads to only a part of the collimated light entering the effective area of the concentrating optics. The part of the light, which is not entering the effective area of the lens, will not hit the converter. It is either absorbed by the lens aperture, or it will hit the area around the converter layer. Based on optical simulation, this geometrical efficiency is expected to be around 90% in an optimal case. The rest of the light is concentrated onto the surface of the converter layer, which comprises a refractive index of approximately 1.8. Therefore, about 8% of the light will be reflected by the surface due to Fresnel reflection. Owing to the material properties of the used converter ceramic, it is expected that backscattering of the blue light hitting the converter only plays a very minor role. Hence, it is not considered in this theoretical calculation.

The efficiencies along the optical path are summarized in Table 2. It can be seen that the flux entering the converter layer is anticipated in the range between 54% and 70% depending on the collection angle of the optics. This means that the luminance of the light source has the potential to be increased by a maximum factor of 1.7 at twice the input power. Consequently, the efficiency is at least decreased by a factor 0.85.

Table 2: Summary of efficiencies in the optical path of the extra blue pump LED and expected relative flux entering the CG layer dependent on the collection angle.

Collection angle	±60°	±65°	±70°	±75°	±80°
Flux collection	75%	82%	88%	93%	97%
Lens reflectance (four lenses)	89%	89%	89%	89%	89%
Dichroic reflectance/transmittance	98%	98%	98%	98%	98%
Geometrical efficiency	90%	90%	90%	90%	90%
CG layer surface transmittance	92%	92%	92%	92%	92%
Blue flux entering CG layer	54%	59%	63%	67%	70%

3 Experiment and results

3.1 Experimental setup

The experimental setup comprises a CG LED (OSRAM LE CG P2A) [7] and a blue LED (OSRAM LE B P2W) [9] of the same size, which were both measured before they were mounted into the setup. A blue LED with a dominant wavelength of 453 nm was used to match the spectrum of the blue LED underneath the converter layer.

Table 3 shows the measurement results and the driving conditions of both LEDs.

The LEDs are mounted onto temperature-monitored heatsinks capable of handling 100 W of thermal power. The pulse current is supplied by an LED driver device (OSRAM RAPCUR F9632D), which is able to drive two channels simultaneously with currents up to 32 A per channel at a frequency of 1000 Hz. The duty cycle can be set via a computer interface. The collimation optics is taken out of

Table 3: Measurement results of the LEDs used in the experimental setup.

	CG LED	Blue LED
Emission area	8.3 mm^2	8.3 mm^2
Driving current	24 A	24 A
Forward voltage	3.49 V	3.41 V
Frequency	1000 Hz	1000 Hz
Duty cycle	50%	50%
Heatsink temperature	40°C	40°C
Dominant wavelength	552 nm	453 nm
Peak luminous flux	7888 lm	688 lm
Peak radiant flux	17.9 W	22.4 W

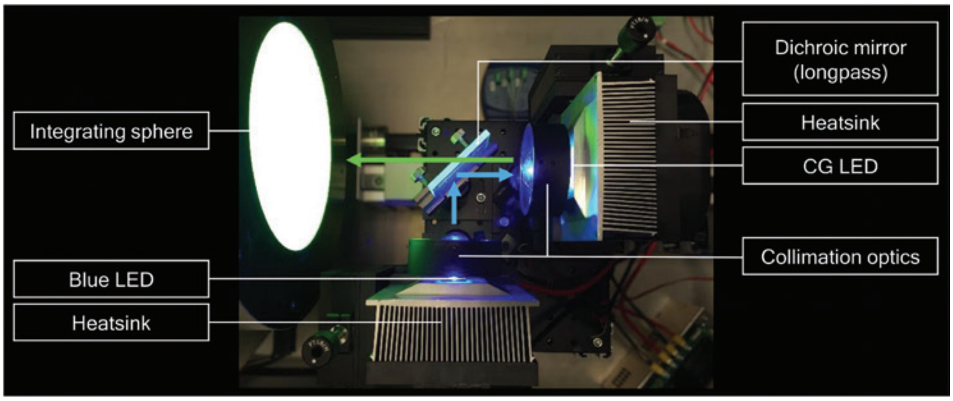

Figure 4: Photo of experimental setup.

an existing projector illumination unit and consists of two lenses, which are mounted into an individually designed housing. The optics' half collection angle is 60°. Topology A, which is shown in Figure 3, is used in the setup. Therefore, the dichroic mirror must be reflective for blue light and transparent for green light. The used mirror (Edmund Optics TechSpec 45° Magenta Dichroic Filter) has its cutoff wavelengths located at 495 nm and 605 nm. Both gaps between the inputs of the optics and the dichroic mirror were fixed to 65 mm. The distances between the LEDs and the collimation optics are optimized during operation in order to maximize the luminous flux at the output.

The radiant flux and the luminous flux emitted by the system are measured with a 500-mm-diameter integrating sphere (Instrument Systems ISP-500) located in the optical path of the CG LED after the dichroic mirror. A photo of the experimental setup is shown in Figure 4.

3.2 Measurement results

The output flux is measured at different driving currents between 8 and 32 A with a pulse frequency of 1000 Hz and a duty cycle of 50%. The fans of the heatsink are operated at full power to cool the LEDs most efficiently. The measurements are performed after the system has reached a stable output flux and a constant heatsink temperature, which did not exceed 31°C during operation. The CG LED and the additional blue LED can be driven independently from each other. Three different driving modes are applied to the system – the CG LED is operated alone, the blue LED is operated alone, both LEDs are operated synchronously. The measured peak luminous fluxes of the different driving modes are shown in Figure 5. Additionally, the sum of the values that are measured, when the two LEDs are operated separately, is shown in the diagram. Information about the color of the various driving modes

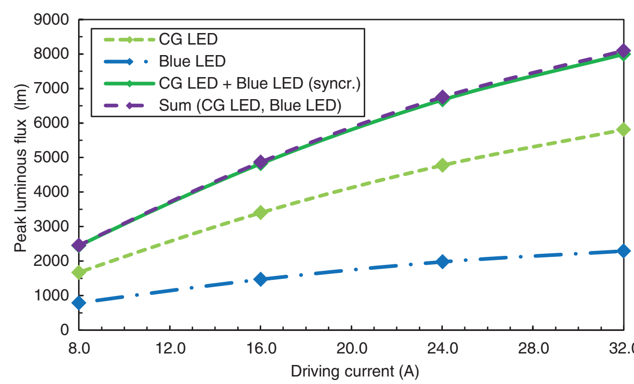

Figure 5: Measured peak luminous flux at the output of the setup vs. the driving current per LED.

is given in Table 4. Because the color coordinates do not change significantly in the observed current range, only the values at a current of 32 A are shown.

The behavior of the radiant flux is illustrated in Figure 6. In addition, the respective values of the blue LED in front of the input aperture of the second pair of lenses (i.e. before it is focused and converted) can be measured by flipping the dichroic mirror by 90°. The results are also shown in Figure 6.

The radiant and the luminous flux at the output rise at all driving modes continuously with increasing current. The luminous/radiant flux of the CG LED rises from 1670 lm/3.11 W at 8 A over 4780 lm/8.86 W at 24 A to 5810 lm/10.76 W at 32 A. The electrical peak power of the

Table 4: Measured spectral data of the three different driving modes at a current of 32 A.

	CG LED	Blue LED	CG + Blue LED (synchr.)
Dominant wavelength	557.5	556.5	557.3
CIE x	0.353	0.345	0.351
CIE y	0.607	0.589	0.602

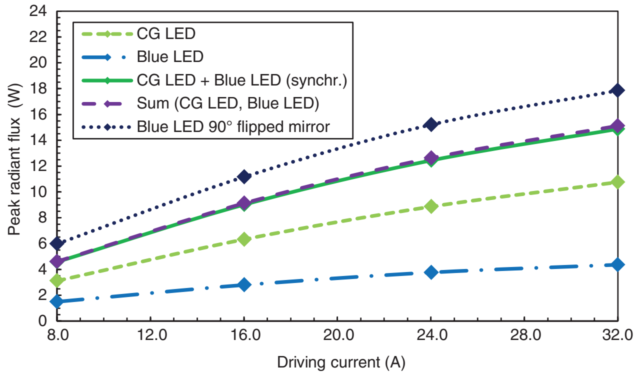

Figure 6: Measured peak radiant flux at the output of the setup vs. the driving current per LED.

CG LED is 116 W. The luminous/radiant flux induced by the blue LED ranges from 790 lm/1.50 W at 8 A over 1980 lm/3.76 W at 24 A to 2290 lm/4.36 W at 32 A. When both LEDs are operated synchronously, the measured luminous/radiant flux ranges from 2440 lm/4.58 W at 8 A, 6670 lm/12.44 W at 24 A and 7990 lm/14.87 W at 32 A. The electrical peak input power at the maximum current is 231 W.

The radiant flux of the blue light reflected by the 90° flipped dichroic mirror rises from 5.89 W at 8 A over 15.21 W at 24 A to a maximum value of 17.85 W at 32 A.

4 Discussion

At current densities between 2 and 4 A/mm^2, a gain between 38% and 42% can be observed. In this current range, the spectral distribution of the blue LED does not change significantly. At a lower current density of 1 A/mm^2, a higher gain of 46% is achieved. That behavior may be attributed to the blue LED having a spectral distribution shifted to longer wavelengths at lower currents [9] and the strong wavelength dependency of the reflectivity of the dichroic mirror [10].

Figures 5 and 6 show clearly that the measured flux driving both LEDs at the same time and the sum of fluxes driving the LEDs individually nearly match each other. The difference between these values is in the range of the measurement uncertainty. Consequently, it can be concluded that the ceramic phosphor material does not show additional quenching or saturation effects within the investigated range.

A channel enhancement factor of about 1.4 is observed, which is lower than the anticipated factor of 1.54. One minor root cause is the lower reflectivity of the dichroic mirror for light emitted by the blue LED. Ninety-eight percent was expected for optimized characteristics. For the used dichroic mirror, only a reflectance of 96% for the blue LED light was determined.

By evaluating the color of the light at the output at the different driving modes, it can be distinctly observed that the color created by exciting the phosphor from the top side is shifted toward the blue region of the color space compared to the color, when only the CG LED is on. Therefore, it can be stated that the amount of blue light being converted to green is much lower than expected, especially when the very low transmissivity of the dichroic for blue light (approximately 4%) is considered. This may be caused by reflections of the blue light hitting the area around the converter. Owing to losses induced by the distances between the components and the output divergence angle of the used optics, the light cannot be concentrated completely onto the converter. Hence, the optimal value for the geometrical efficiency of 90% cannot be reached in the experimental setup. By adapting the simulation model to fit to the geometrical layout of the experiment, a value of approximately 70% can be determined, which fits experimental results well.

In summary, the luminance of the CG LED can be increased by a factor of 1.4 by exciting the phosphor additionally from the top side with an extra blue LED while the efficiency drops by a factor of approximately 0.7. Even though the predicted gain of 54% could not be reached in the experimental setup, it can be confirmed that the presented concept has the ability to increase the luminance of the green light source. It is supposed that further improvements can be performed by optimizing the optical path, increasing the collection angle, and decreasing the output divergence angle.

For the applicability of the concept, it is important to evaluate the influence of the additional blue light on the reliability of the CG LED. Both the ceramic converter and the LED below are exposed to additional stress. The temperature of the converter platelet and the LED junction reach slightly higher values compared to normal operation. Moreover, additional aging effects induced by the higher blue flux level cannot be excluded. Although the used LED did not show any exceptional behavior during operation, a clear statement concerning lifetime cannot be given without any appropriate long-term reliability test.

5 Application proposal

The shown concept may be integrated in a projector illumination unit without making major changes on the system. The additional blue LED and its optics can be installed on

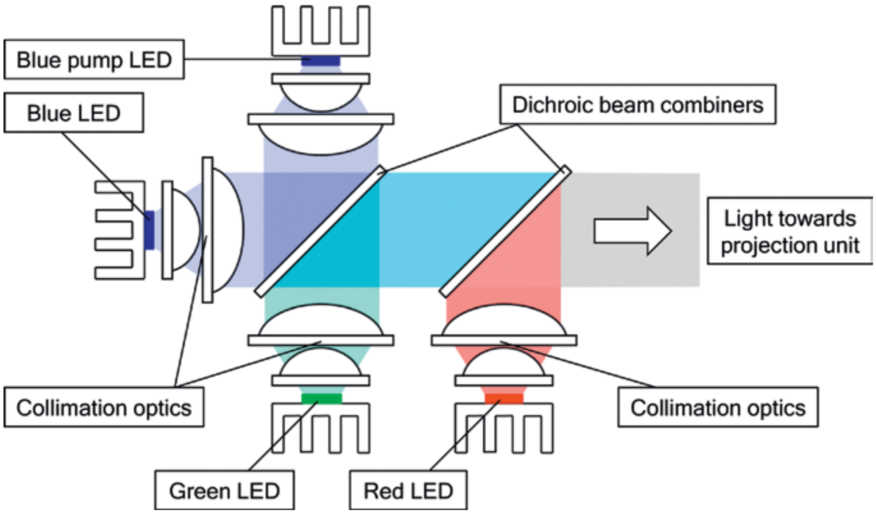

Figure 7: Concept applied to a common projector topology.

the other side of the mirror, opposite the CG LED without affecting the existing optical path. The concept applied to a common illumination unit (see Figure 1) is schematically shown in Figure 7.

6 Conclusion

In this paper, a new concept was introduced that is supposed to increase the luminance of a CG LED by exciting its ceramic phosphor platelet additionally from the top side by an extra blue LED. The experimental setup was able to create green light with a low divergence angle, a peak luminous flux of 8000 lm, and a dominant wavelength of 558 nm. The light originated from an emission area of 8.3 mm^2, while a peak input power of 231 W was applied to the system. An enhancement factor of 1.4 was experimentally shown. The system comprised, besides the LEDs, a dichroic mirror and suitable lenses to collect and collimate the light of the LEDs.

The presented concept may be applied to the topology of an existing projector illumination unit without performing major changes on the system. An increase of 40% in the green channel of a projector is expected to lead to a gain of approximately 15% in white luminous output flux, while maintaining a white point according to Rec. 709. However, that gain is accompanied by an efficiency decrease in the green channel of a factor of 0.7. Optimizing the optical path by adapting the optical components is anticipated to result in significantly higher gain values for the green channel of up to a range between 60% and 70%, which would lead to an approximately 20% higher projector flux.

The concept might also be applied to the red light source if a suitable conversion material is used. Furthermore, the concept can be used to increase the luminance of a converter LED comprising a yellow phosphor and mixing it with additional blue light to create a high luminance white light source.

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