A High Power Blue Diode Laser Pumped White Light Source Using Remote Phosphors

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Abstract

Bright white LEDs are rapidly changing the traditional automotive headlamp architecture based on halogen lamps or the more recent HID lamps. For the next generation of automotive front lighting, a diode laser pumped remote phosphor based white light source can be even better in terms of brightness, efficiency, and design flexibility. A diode laser uses smaller optics, opening the possibility for compact arrayed systems for adaptive beam shaping. On top of that, the remote phosphor architecture separates the laser and the phosphor, which improves thermal management as well as modular design flexibility. Given the wide range of phosphors available commercially, it can be quite difficult to choose the right one in terms of efficiency, colour rendering and durability under blue (~ 450 nm) laser irradiation. Hence it is of great importance to systematically study a wide range of such phosphors for optimal performance. In this paper, a high power blue diode laser (> 1 W) pumped remote phosphor based white light source is presented with a comparative study on various phosphors, in terms of efficiency, colour rendering properties and temperature stability.

1 Introduction

Ultra-bright white light-emitting-diodes (LED) are much more efficient than halogen lamps and hence are rapidly capturing the market for general illumination. LEDs are also replacing halogen lamps or even newer Xenon lamps in the automotive headlamps. A typical white LED is made of a blue LED chip covered by a phosphor coating. Due to phosphorescence, a part of the blue light absorbed by the phosphor is frequency-down converted to a wide band of spectrum from green to red, and this being mixed with the unconverted blue light gives a white light output with a certain correlated colour temperature (CCT) [1].

Since laser diodes are inherently much brighter [2] and usually more efficient than LEDs, there has been an enormous interest to develop high power blue laser diode systems. Blue laser diodes and phosphor based white light engines are already integrated in various commercial multimedia projectors. In 2011, BMW first demonstrated a blue laser based headlamp using remote phosphor in the i8 concept car [3]. The system was reported to be much brighter and efficient, as compared to typical LED counterparts [3]. In the Consumer Electronics Show 2013, Audi displayed its laser tail light [4]. Recently, in the Shanghai Motor Show 2013, Mercedes-Benz unveiled its GLA™ concept sport utility vehicle (SUV) with a laser projection based front lighting system [5]. Hence, it is evident that the automotive industry is keenly considering laser based lighting solutions for future. A smaller form-factor of a laser based lamp will offer greater design flexibility and more space for the engine and other mechanical parts. However, discomfort glare is a well-known problem in xenon or LED based headlamps and very often it is blamed on the excessive bluish colour tone of the light [6]. While using a remote phosphor architecture, one can always benefit from the possibility of changing the particular remote phosphor and, as a result, change the colour temperature of the output light.

Remote phosphors are known for exceptional optical design flexibility and thermal management, due to the physical separation of the optical pump source (blue LED or laser diode) and the phosphor module [7]. The promising design aspects of a laser pumped remote phosphor based automotive headlamp were presented in [8].

Driven by the future potential of laser based automotive headlamps, we developed and characterized a 1.4 W laser diode (LD) pumped remote phosphor based white light system and also built a laboratory prototype of a headlamp.

2 System development and characterization

A 1.4 W ~ 450 nm LD (PL TB450 from OSRAM) was used as the optical pump source [9]. Commercially available ChromaLit™ remote phosphors from Intematix® Corp. were used in all the experiments [10]. Intematix® suggests that these ChromaLit™ samples should be considered as engineering prototypes only and for any particular product development these phosphor modules can possibly be further redesigned for optimum performance [11].

For the optical characterization of such phosphor modules, an integrating sphere based test-bed was used. In order to verify the optical characteristics of the ChromaLit™ products, preliminary tests were performed using a demo-kit, CL-DEMOKIT-2D-PC, with various phosphor plates. This commercially available demo kit is a small device with a circular

array of blue LEDs embedded in a white mixing chamber [11]. A circular phosphor plate can be affixed on top of the mixing chamber so that it is illuminated by the LEDs beneath.

The spectral characteristics of the white-light output from the demo-kit, with various phosphor modules, are compared in Fig. 1. The measured CCT and colour rendering index (CRI) for each sample are compared to the corresponding nominal values in Table T1. As evident from T1, the experimental values are in good agreement with the corresponding nominal values specified in the ChromaLit™ data-sheet. This also confirms good calibration of the integrating sphere and the spectrometer (Labsphere SMS-500) attached to it.

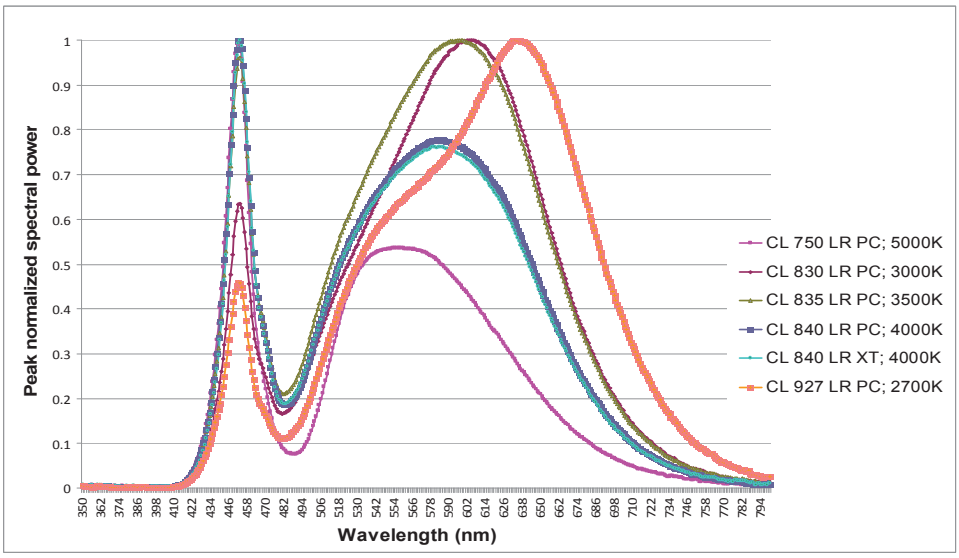

Fig.1 White light spectra from various ChromaLit™ samples with the LED based demo-kit

Phosphor sample	Nominal CCT (K)	Measured CCT (K)	Nominal CRI	Measured CRI
CL 750 LR PC	5000	5201	70	~ 71.5
CL 830 LR PC	3000	3056	80	~ 81.1
CL 835 LR PC	3500	3516	80	~ 81.6
CL 840 LR PC	4000	4054	80	~ 80.8
CL 840 LR XT	4000	4069	80	~ 80.7
CL 927 LR PC	2700	2756	90	~ 91.1

Table T1: White light characterization of the ChromaLit™ remote phosphor samples mounted on the LED demo kit [11]

The ChromaLit™ products are available in both polycarbonate (PC) and glass (XT) substrates. For the experiments with the blue LD, glass substrate based phosphor modules were chosen only, in order to avoid potential laser induced damage.

The operational current and voltage points for the LD were set to 1200 mA and 4.62 V respectively. The optical output power was ~ 1.38 W (after a collimator) and the peak wavelength was ~ 447 nm.

The entry of the collimated laser beam into the sphere was made through a small aperture port. The ChromaLit™ phosphor module was placed on a small tray inside the sphere in such a way that the omnidirectional phosphorescence could be optimally reflected by the inner spherical wall and collected at the detector. Note that such an experimental configuration differs from the guideline (by Intematix®) for mixing chamber design (with LEDs) and hence the measured CCT values can be significantly different from the nominal CCT values mentioned in the datasheet. However, as long as the white light generated from such an arrangement falls within the standard white boundary [12], that can be acceptable for automotive illumination applications. For the laser pumped experiments, only two ChromaLit™ phosphors with nominal CCT values of 4000K and 5000K were used. Other phosphor samples (2700K, 3000K and 3500K) which came bundled with the LED demo kit were not used for the laser experiments as they had polycarbonate substrates instead of glass. Also, such low CCT phosphors (2700K-3500K) might not be suitable for automotive headlamps. The best results obtained so far, in terms of the conversion efficacy of radiation (CER), are shown in Table T2. Note that the CER (lm/W_{rad}) is defined as total lumens generated per unit optical power irradiated by the blue source concerned. The measured chromaticity coordinates of the white light sources are compared in Fig. 2. The textual marking beside each measured point shows the product number, nominal CCT and the pump source (LD or LED).

Phosphor number	Nominal* CCT (K)	Measured CCT (K)	Nominal CRI	Measured CRI	Nominal CER (lm/W_{rad}) typical	Measured CER (lm/W_{rad})
CL 750 XT	5000	6349	70	~ 70.3	230	~ 249
CL 840 XT	4000	4629	80	~ 75.1	218	~ 235

*Table T2: White light characterization of laser pumped remote phosphor samples (*nominal CCT, CRI and CER [13] are valid for LED pumped systems with suggested mixing chamber design and not meant for our customized laser pumped system)*

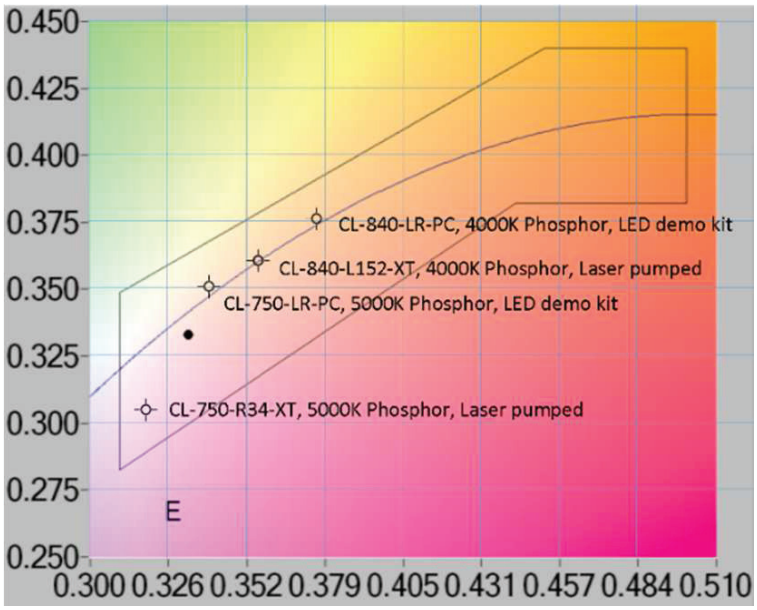

Fig.2 Chromaticity coordinates (x, y) of the white light generated by various phosphors under LED or LD irradiation [12]

Note that, in a previous experiment where the thermoelectric cooler (TEC) temperature of the LD was varied from 15 °C to 30 °C, the best CER was obtained at 15 °C. The output lumens fell down by ~ 8% as the TEC temperature was increased from 15 °C to 30 °C. Hence, the laser experiments reported here were performed with TEC temperature set at 15 °C for optimal CER in the said temperature range. However, it should be clarified the LD chip must have been at > 15 °C in thermal equilibrium condition as the TEC element is not in direct contact with the chip. The temperature gradient from the chip to the heat sink is subject to further experiments and thermal simulations. The variation of output lumens with the TEC temperature could be due to the shift in peak wavelength of the laser diode [14]. However, the measurement of the shift in peak wavelength (of the order of sub-nm/°C) with the variation of TEC temperature was not possible in our set up, due to the resolution limitation (1.5 nm) of the existing spectrometer. Note that, with the variation of temperature, the threshold current and output power of the laser diode would also vary.

In order to understand the thermal condition of a phosphor sample under the blue laser irradiation, a thermal imager (FLIR Systems - ThermaCAM S40) was used to monitor the rise in temperature from the point of switching on the LD. Fig. 3 shows the rise in temperature with respect to the time elapsed after the laser was switched on, the equilibrium state and also the drop of temperature after switching off the laser. The maximum temperature was ~ 47.6 °C.

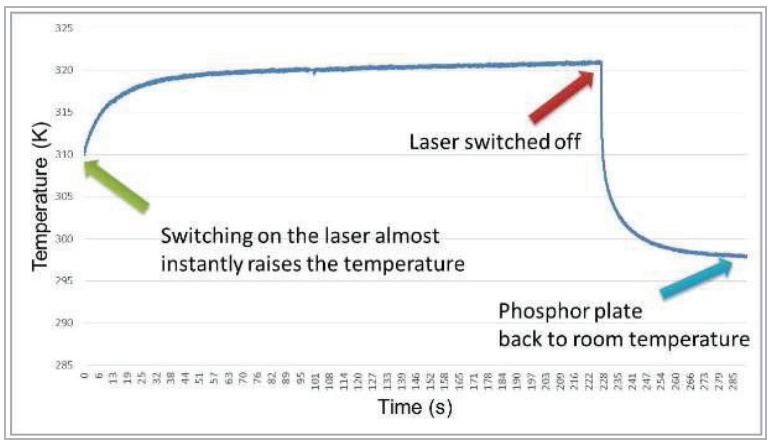

Fig. 3 Temperature dynamics of the 5000K phosphor sample

Excellent temporal stability of the output lumens and CCT of the 4000K and 5000K ChromaLit™ phosphors are shown in Figs. 4 and 5. For the 5000K phosphor, the experiment was repeated for a longer duration and the results are also shown in Figs. 4 and 5, reconfirming excellent stability. The legends are marked with the nominal CCT values of the respective ChromaLit™ remote phosphor modules.

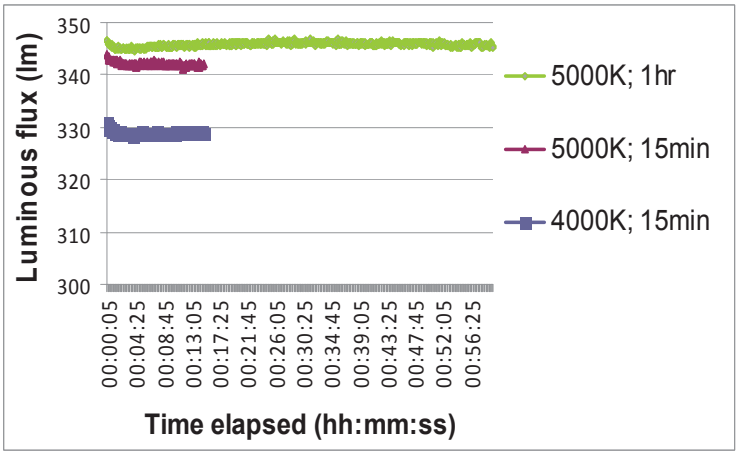

Fig. 4 Temporal stability of output lumens generated by the phosphor samples under laser irradiation

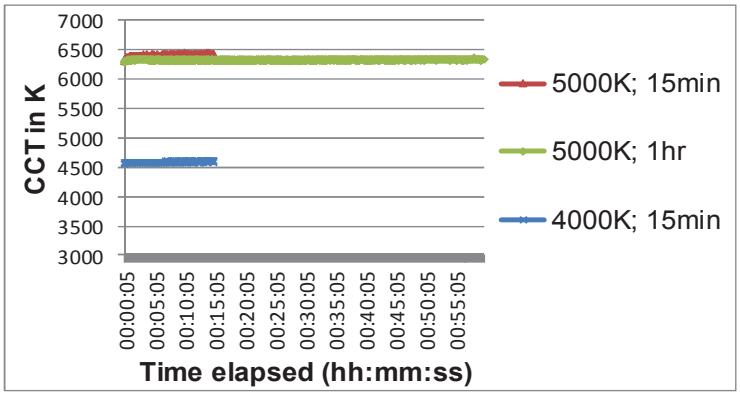

Fig. 5 Temporal stability of the output CCT from the phosphor samples under laser irradiation

Spectral characterization of different white light sources is an integral part of our research on future automotive lighting systems. White light spectra from a commercial xenon headlamp system, the LED demo kit with 4000K phosphor and the blue laser pumped 4000K phosphor are compared in Fig. 6.

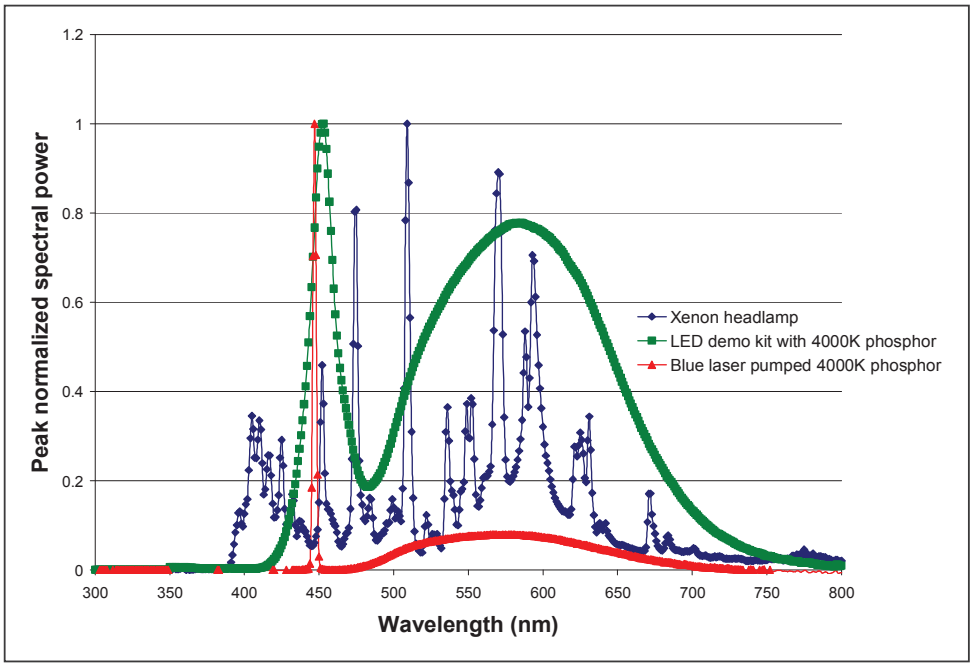

Fig. 6 Spectral characteristics of three different white light sources

There is a misconception that laser based light sources may not offer good colour rendering due to the narrow linewidth of the laser sources. However, it has been demonstrated, in a four colour laser mixing approach (R, G, B and Y), that the output white light rendered very good colours, contrary to the common belief [15]. Since the white light spectra from the same phosphor under LED and LD pump look significantly different as shown in Fig.

6, the colour rendering property of the laser based white light source was also verified by taking photographs of a variety of fruits illuminated by that source. The same approach was repeated for illumination under different white light sources. The SONY A290 camera used in these cases was always kept at ISO 200 and preset daylight white balance. The camera was mounted on a tripod and the aperture priority mode was used for every snapshot. The photographs of the fruits under different illumination conditions are compared in Fig. 7. The corresponding white light sources are mentioned below.

Fig. 7 Top row - Light sources (from left to right): The laser-headlamp prototype (4000K phosphor), a commercial Xenon headlamp, and the LED demo kit with 4000K phosphor
Bottom row – Light sources (from left to right): The laser-headlamp prototype (5000K phosphor), a tungsten halogen lamp, and a fluorescent tube light system (ceiling)

A part of our headlamp prototype and the low beam light distribution pattern can be seen in Fig. 8 below.

Fig. 8 (left) Photograph of a part of the headlamp prototype along with the low beam pattern formed on a screen; (right) Isolux pattern of the headlamp, created out of a photograph

It must be noted that luminous efficacy (lumen/electric power input) of such a system can dramatically improve with the advancement of InGaN laser diode technology. The InGaN based multi-quantum well (MQW) blue laser diode technology is not as mature as that of its near-infrared (NIR) counterparts like 808, 915 or 976 nm LDs. For an example, a 975 nm laser diode can generate 25 W of output at roughly 54.6 W of input electrical power, amounting to ~ 46% wallplug efficiency [16]. However the blue laser diode used in our experiments could generate maximum 1.4 W of CW output power at 5.54 W of input electric power, that is ~ 25.3% wallplug efficiency (WPE) with TEC set at 15 oC. It is worth mentioning here, as a reference, that the product release note quoted 27% WPE while generating 1.4 W of output power at room temperature and a current of 1.2 A [9].

In a report on InGaN based blue laser diodes by Soraa Inc., an increase in the WPE from ~ 1% to over 23%, within the period between April 2009 and June 2010, while the output power increased over 750 mW, was mentioned [17]. In May 2011, Soraa Inc. reportedly achieved a maximum output power > 1.4 W with WPE > 21% [17]. Such a trend is very promising for practical applications of laser pumped phosphor systems in near future.

Also, the remote phosphors may be specifically re-designed in order to achieve maximum luminous efficacy under blue laser irradiation. Note that the ChromaLit™ catalogue products used in our experiments were not particularly designed or recommended for laser pumped applications.

3 Discussion & conclusion

A 1.4 W blue diode laser pumped remote phosphor based white light system was developed and characterized. Performances of different remote phosphor samples were compared. The ChromaLit™ remote phosphor samples were thermally stable under laser irradiation, as evident from the temporal stability of the output power and CCT of the white light

output. CER of ~ 249 lm/W_{rad} and ~ 235 lm/W_{rad} were obtained from two different remote phosohors under the 447 nm blue laser irradiation. Spectra from different white light sources, including our laser pumped phosphor headlamp prototype, were compared along with the photographs of some fruits illuminated by those sources. The colour rendering by our headlamp prototype appeared to be quite balanced and even better than that from a commercial Xenon headlamp. This is a very promising aspect and ensures that laser pumped phosphor based headlamps can offer good visibility of various coloured objects to naked eyes. The overall system efficacy (lm/W_{elect}), i.e. the output lumens per unit input electric power, was grossly dominated by the wallplug efficiency of the laser diode. Note that, the ChromaLit™ catalogue products used in our experiments were not optimally designed for laser pumped applications. Hence, even further improvement in efficiency and colour rendering may be feasible with custom designed remote phosphors. The study presented here strongly emphasizes on the possibility of laser pumped remote phosphor based white light sources being utilized for versatile applications, including automotive headlamps, in near future.

4 Acknowledgements

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