Etendue maintained white solid-state light generation by light emitting diodes pumped green aluminate green-yellow phosphor

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Abstract. We propose a technique to generate etendue maintained white light. The proposed technique uses three high-power blue light emitting diodes (LEDs) with identical characteristics to pump green aluminate (GAL) green-yellow phosphor coated on the inner channel of a waveguide. The technique offers two methods of generation of white light. Standalone partial conversion of blue to green and yellow light by GAL phosphor, combined with unconverted blue light, produces white light homogenized within the light guide. Complete conversion of blue to green and yellow light with the further addition of blue and red wavelengths from additional LED sources multiplexed with the output is also possible to further increase total white light output. Following design and optical modeling to prove the concept, the proposed technique is demonstrated, which shows white light emissions from the waveguide with no increase in aperture size while the original LED etendue is maintained. The proposed technique offers an alternative to low-lifetime, low-efficiency xenon lamps for light sources in etendue critical applications such as endoscopy. © *2021 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.60.2.025104]

Keywords: photonics; light emitting diodes; phosphor; multi-pumping; etendue-maintained.

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1 Introduction

The interest in high-brightness efficient white light sources has increased in recent years with etendue critical applications, such as endoscopy. Light source technology is progressing from incandescent and gas discharge lamps to more efficient solid-state lighting sources due to their increased energy efficiency, longer lifetimes, and reduced cost.[1] They are already being increasingly used for a number of broad area illumination applications[2,3] leading to the interest in applications with restricted etendue. Laser sources for example are known to have low-etendue advantages due to their ability to be collimated with a small spot size, leading to high current densities.[4] Developments in indium gallium nitride light emitting diode (LED) technology has led to an increasing wall plug efficiency of >80% for blue emitting LEDs[5] meaning the emitting area can be reduced, in turn reducing etendue while still achieving a relatively high radiant output.

Blue lasers have been used in multiple applications to achieve low-etendue white light.[6,7] With a high-optical intensity pumping onto powdered phosphor, the small laser spot size suggests that etendue restricted applications are suited but its high-power density can result in overheating of the phosphor due to unconverted absorbed light producing heat, resulting in thermal quenching and the phosphor breaking down. Typically, this is overcome using a spinning wheel technique, which reduces the time the phosphor is allowed to heat up, therefore, keeping the phosphor intact.[8] This type of solution addresses the lamp and phosphor lifetime issues but introduces a lifetime issue of its own due to the bearings of the spinning wheel becoming worn. In time, the worn bearing causes fluctuations in the optical path length, resulting in distorted outputs.

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To solve the issue of overheating of phosphor caused by the laser, LEDs are considered as good candidates to replace lasers to generate white light due to their increased efficiency, low-power consumption, longer lifetimes, a relatively low etendue and most importantly, the increase of the illumination area on the phosphor, therefore, reducing the intensity per unit area to avoid the overheating problem. Light from the LED in the blue wavelength range distributed over the phosphor area is absorbed by the phosphor green aluminate (GAL) material bringing about electroluminescence through electron excitation and a conversion to yellow-green light. However, the maximum output intensity of blue LEDs does not meet the requirements needed by high-intensity applications such as endoscopy.

Optical pumping of solid ceramic YAG:Ce and LuAG phosphor material with high-intensity laser light to increase luminous intensity has previously been explored,[9,10] with a generated luminous efficiency of up to 101 lm/W. LED multi-pumping of solid phosphor rods has also been investigated,[11–14] where solid transparent phosphor rods of YAG:Ce or LuAG are formed into a light guide. Multiple blue pump LEDs are positioned along the length of the light guide and used to excite phosphor particles within the solid structure. Emitted light from the phosphor travels along the light guide with total internal reflection being the mechanism to reflect light with an angle of incidence within a critical angle internally from the outer surfaces until eventually reaching the exit face. Investigation of these techniques highlights advantages in providing relatively stable structures with an optical efficiency of ~8%. The limitations of both the laser and LED pumped variations unfortunately are that currently crystal and ceramic structures are only available in a limited number of phosphor materials, such as Ce:YAG and LuAG and so are limited to the wavelength spectrum they produce. The light guide is made solely of one material, so it is currently not possible to mix various phosphors or vary the amount of phosphor to tailor the amount of blue that can pass through to produce white light of varying CCT. The light guide being made of the solid phosphor material also results in reabsorption of converted light, which reduces efficiency.

In this paper, to utilize the improving LED technology but overcome its limiting issues, multiple LEDs with identical optical characteristics are combined to increase the overall output. Etendue is, however, maintained by keeping the system output aperture and emitting angle identical that of the LEDs, making the technique suitable for etendue restricted applications.

This paper is organized as follows. In Sec. 2, we first describe the concept of how multiple LEDs are combined in one system without increasing etendue. In Sec. 3, we simulate the concept with Zemax Optical Studio providing a predicted result. In Sec. 4, the experimental arrangement, describing setup, and measurement details are provided, and in Sec. 5 we conclude this paper.

2 Concept

To achieve the proposal of increasing the number of LEDs to increase the output, multiple LEDs with identical characteristics are arranged around a high-reflective hollow light guide to pump a green-yellow GAL (aluminate) phosphor coated internally on the high-reflective coating. Specialist dichroic filters are used to allow the blue light to enter the light guide while reflecting the yellow-green emitted light from the phosphor, keeping it within the light guide. The combined blue and yellow-green light homogenize within the light guide to produce white light. The hollow arrangement reduces the chances of reabsorption, which only occurs when converted light makes contact with the sections of coated phosphor further along the light guide. The high-reflective hollow light guide combines the light from the LEDs while keeping the entrance and exit apertures identical to that of the LED. This along with the same Lambertian divergence distribution maintains the etendue of the LED to keep efficiency as high as possible. An illustration of the design is shown in Fig. 1.

In Fig. 1, a four-sided high-reflective glass light guide, {1} is assembled to collect and homogenize light from all inputs. Dichroic glass filters {2}, {3}, and {4} are designed to allow light in the blue spectral wavelength range to transmit while reflecting light in the yellow-green wavelength range are used as entry points for the blue LED light. The dichroic filter {2} is coated with phosphor {5} providing conversion from blue light to broadband green-yellow light into the light guide. The phosphor is excited by light from blue LED 1 {8}, forward emission into the

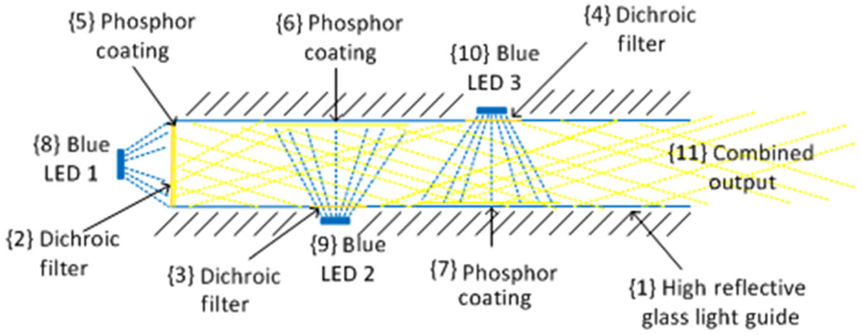


Fig. 1 Etendue maintaining high-reflective multi-LED pumped phosphor concept.

light guide is contained by the high-reflective glass while rear emission from the phosphor is reflected by the dichroic filter also back into the light guide, collecting additional light that would originally have been lost. Phosphor coatings {6} and {7} are initially pumped by blue LED 2 {9} and blue LED 3 {10}, respectively, and are coated on the opposite side of the light guide to the LEDs in order to help spread the output power from the LED to reduce the intensity and the possibility of overheating the phosphor, in these locations. This method also allows for varying phosphor types to be used within the same light guide to vary the wavelength spectrum and also tailor the amount of phosphor to increase the amount of blue light throughput to produce a combined white light total output.

3 Numerical Simulations

A commercial simulator (Zemax Optic Studio) based on the Monte-Carlo method[15] is used to perform the numerical simulations of the above design.

The phosphor emission spectrum provided by the manufacturer as shown in Fig. 2 is used to define the phosphor characteristics in the simulations. Three Luminus Devices PT-121-B LEDs are simulated and arranged around the outside of the hollow light guide as shown in Fig. 1 to excite the phosphor coated on the high-reflective inside surface. Predictions of luminous flux, wavelength spectrum, and optical uniformity at a detector placed at the exit of the light guide and calculated by the simulation software. The simulation outputs of (a) wavelength spectrum and (b) uniformity are shown in Fig. 3 with an overall luminous flux at the exit of the hollow light guide of 3720 lumens of green-yellow light and a luminous efficiency of 89 lm/W compared to the optical input power to the system provided by the blue source LEDs.

The etendue of the LEDs is calculated as 27.11 mm^2 using the following equation:[16]

$$G = n^2 \pi A \sin^2 \alpha, \tag{1}$$

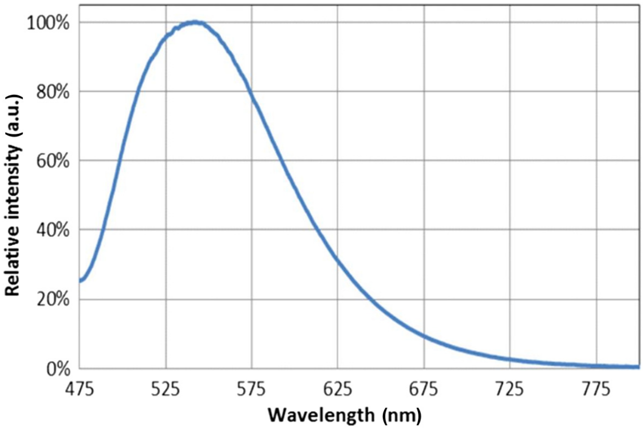
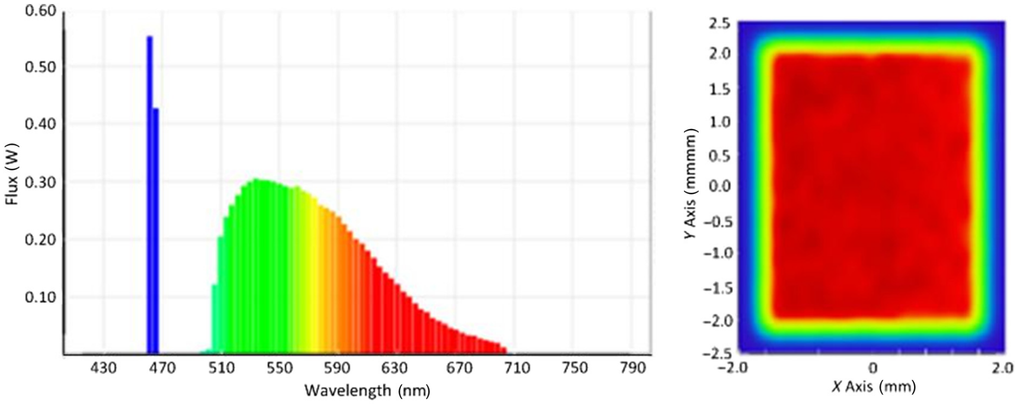


Fig. 2 GAL phosphor spectrum.



(a) (b)

Fig. 3 Zemax modeling (a) spectral output and (b) uniformity at light guide exit.

where G is the etendue, $n = 1$ is the refractive index of the medium (air), $A = 12\ \text{mm}^2$ is the area of the emitting aperture, and $\alpha = 58\ \text{deg}$ is the half acceptance angle into the aperture, as stated by the manufacturer.

For a suitable high-power multi-laser diode array as used in white light phosphor systems,[17] the collimated beam is found to be $4\ \text{mm}^2$, resulting in an etendue of $9.04\ \text{mm}^2$. Although this is lower than that of the LEDs, the small spot size results in a high-power density and thermal quenching of the phosphor without a spinning wheel cooling technique.

4 Experiment

GAL540 GAL-based phosphor from Intematix Inc. is chosen due to its high thermal stability of 90% luminosity at 200°C, thermally more robust than standard YAG:Ce phosphor used in white LEDs for solid state lighting, which falls to 70% luminosity at 200°C.[18] Nusil LS26140 silicone is used as an encapsulant due to having an optical transparency of >90% over the visible wavelength range and also being thermally stable at over 200°C. The blue LEDs are PT-121-B models from Luminus Devices.

To determine the ratio of phosphor to encapsulant to use, various ratios were trialed by mixing controlled amounts of each and spin coating the mixture onto a high-reflective glass substrate and pumped with blue light. The generated green-yellow output is captured in a Sphere Optics LCS-100 integrating sphere and measured to provide a comparison. Examples of the results of the trials found to provide the best performance are shown in Table 1. Corresponding measurements of the wavelength spectrum are shown in Fig. 4 and luminous flux output with increasing LED operating current in Fig. 5.

Of the samples trialed, a mixture of 0.9 g of phosphor to 0.2 g of encapsulant was found to provide the highest green-yellow phosphor output, relating to the highest conversion from blue

Table 1 Examples of phosphor to encapsulant mixing ratios

Sample	GAL540 phosphor (g)	Nusil LS26140 (g)
22	0.2	0.2
23	0.3	0.2
24	0.5	0.2
25	0.9	0.2
27	1.2	0.2

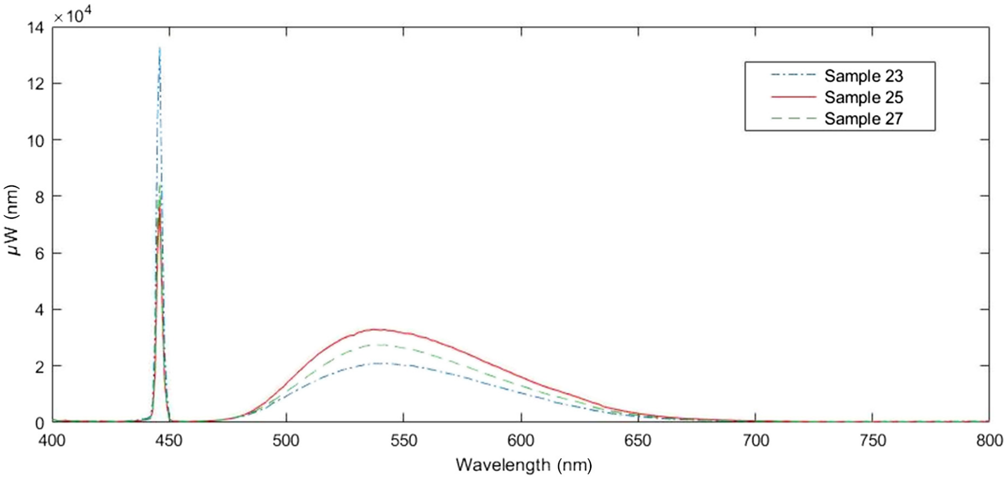


Fig. 4 GAL540 phosphor:LS21640 encapsulant mixing ratio characterization—spectral response.

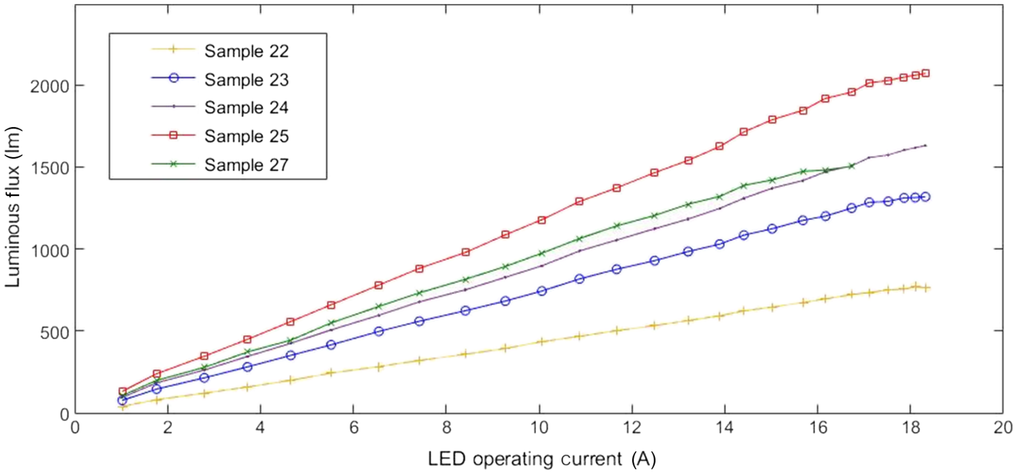


Fig. 5 GAL540 phosphor:LS21640 encapsulant mixing ratio characterization—luminous flux output

pump light to yellow-green phosphor output Fig. 4 resulting in the highest luminous flux output Fig. 5.

To contain light within the light guide, a high-reflective protected aluminum, Visible-99 coating from Comar Optics Ltd., is chosen to coat the internal faces, providing over 99.5% reflection over the wavelength range. Entry points to the system are via windows optically coated with a dichroic filter, EO 500 sourced from Edmund Optics allowing light in the blue wavelength range to enter and reflect light in the green-yellow range generated inside the light guide by the phosphor, shown in Fig. 6.

Custom designed components for the high-reflective light guide not available off the shelf are made from a single piece of 3-mm-thick 62 × 62 mm Visible-99 coated glass, ground down to 1-mm-thick and cut to 62 × 4 mm by Disco GmbH, as in Fig. 7.

A coating of the GAL540 phosphor and Nusil LS21640 encapsulant in the highest performing ratio found in testing, shown in Figs. 4 and 5, is coated onto the cut high-reflective strips by a spin coating method to achieve a uniform even layer. The spin coated layer is restricted to 14-mm in length, shown in Fig. 8 to cover the area illuminated directly by the pump LED situated opposite.

A rectangular cross-sectioned hollow light guide is assembled from the high-reflective glass pieces using a custom designed assembly jig and Dymax Op-29 GEL UV curing adhesive to allow careful positioning before fixing the pieces in place. 4 × 3 × 1 mm pieces of EO 500

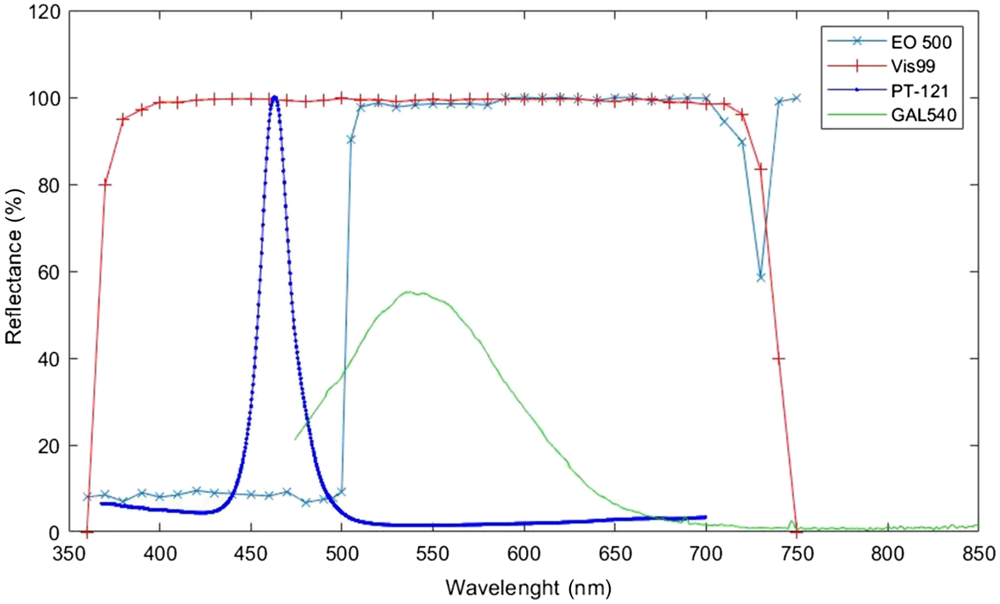


Fig. 6 EO 500 and visible-99 coatings reflectance with relative PT-121 pump LED and GAL540 wavelength spectrum for reference.

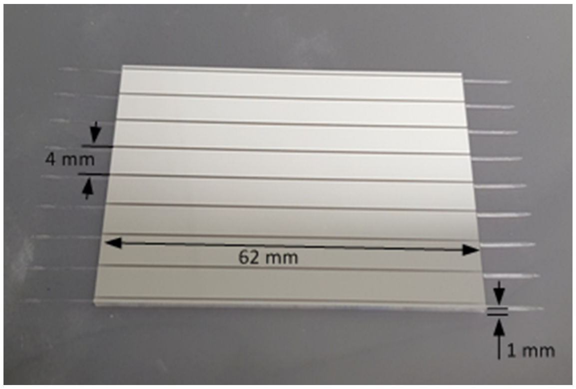


Fig. 7 Visible-99-coated glass ground and cut to 62 × 4 × 1 mm.

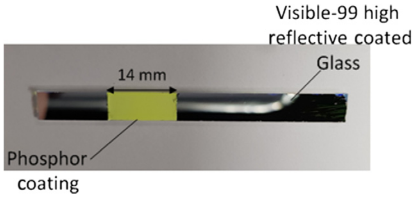


Fig. 8 Spin-coated phosphor on high-reflective coated glass strip.

dichroic filter are used for the entry windows with the phosphor and encapsulant mixture found to be the highest performing out of the samples, spin coated onto the filter face of one piece for the entry window shown as {2} in Fig. 1.

Thermal management of the PT-121-B LEDs is achieved through an assembled cooling device consisting of an Adaptive Power Management GM250 Peltier cooler, a Thermoelectric Devices TDEX6015/TH12G heatsink, a fan, and a copper heat distribution plate and is monitored by an onboard Murata NCP18XH103J03RB thermistor.

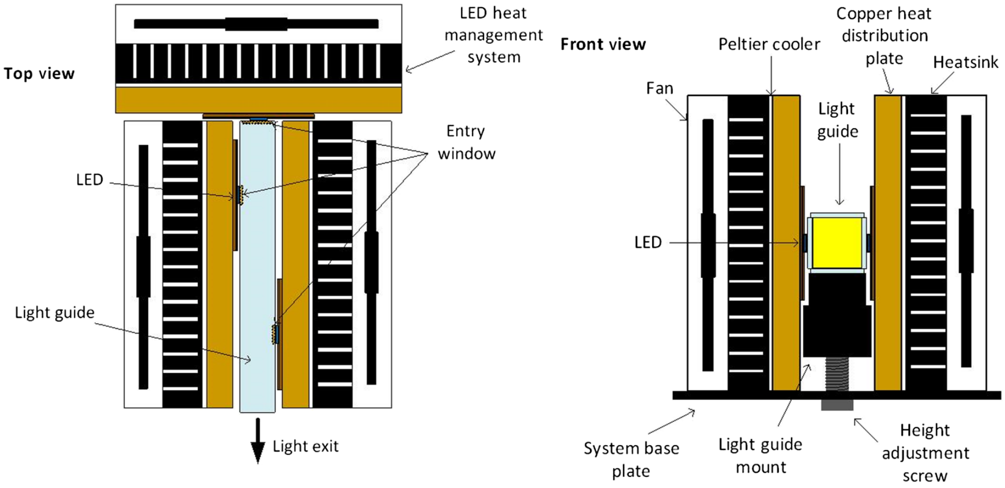


Fig. 9 Top and side view of system setup.

4.1 *System Setup*

System setup comprises three Luminus Devices PT-121-B LEDs assembled onto their heat management system. The three LED assemblies are then placed around the high-reflective phosphor light guide as in Fig. 9. Careful lateral alignment of the LEDs and light guide entry windows and vertical height adjustment by an adjustable mount maximizes efficiency. Actual system photographs of the system setup in operation are shown in Fig. 10.

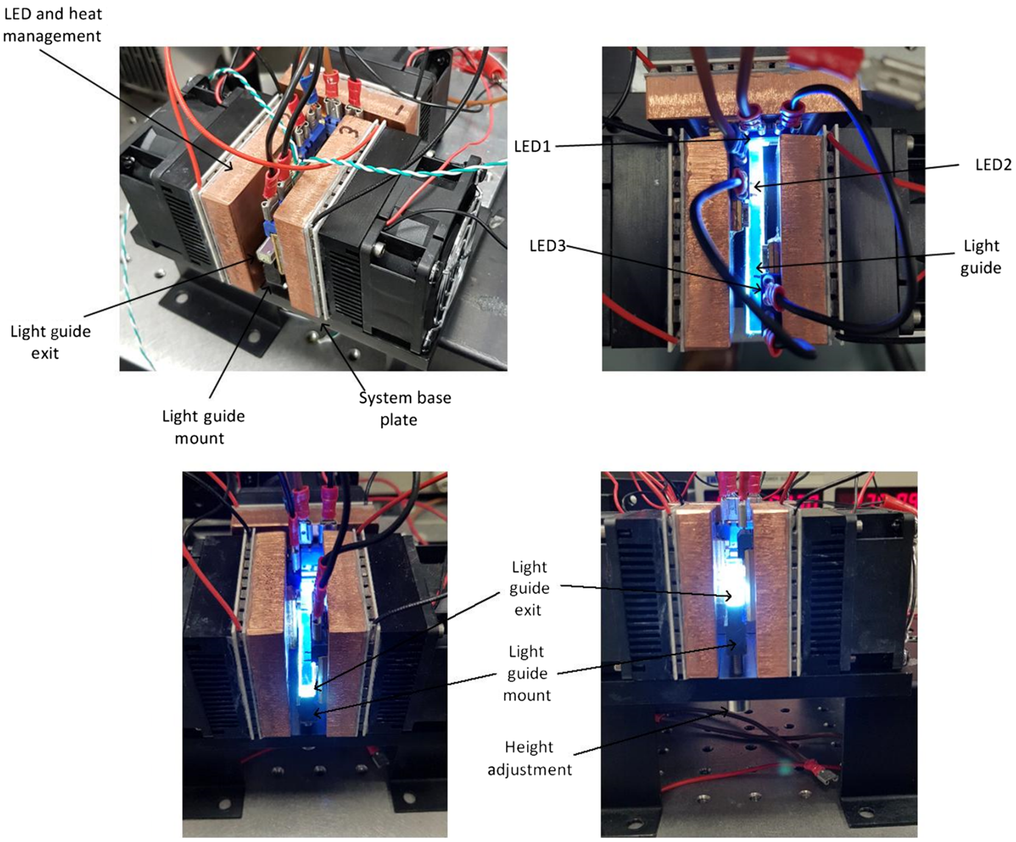
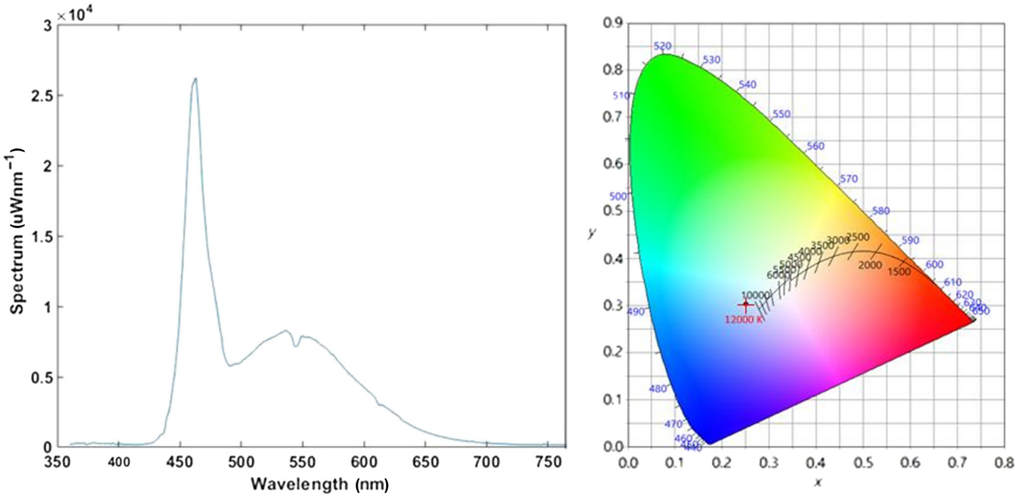


Fig. 10 Photographs of operational system.



(a) (b)

Fig. 11 (a) Wavelength spectrum and (b) 1931 CIE color space chart with CCT of 12,000 K noted by red cursor at exit of multi-pumped hollow phosphor system.

4.2 *Measurements*

System efficiency is optimized through multiple iterations of adjustment of position of the surrounding LEDs to achieve the optimum intended alignment and the corresponding maximum output recorded for this study. Measurements are taken at the exit of the hollow light guide where they are recorded by a LabSphere LCS-100 integrating sphere system. Calibration with a known calibration lamp and corresponding lookup file, with the system in place, considers surrounding conditions such as ambient light to measure just the output of the system.

Output of the system is seen as white light with a broadband green-yellow emission from the phosphor and a blue peak from the LED, with a correlated color temperature, CCT measured as 12,000 K. Wavelength spectrum and the corresponding 1931 CIE Color Space chart are shown in Fig. 11 with the LLG output color shown by the cursor. The output luminous flux measurement with varying LED current is shown in Fig. 12. A luminous flux measurement of 748 lm was measured at 9.5-A pump LED operating current.

4.3 *Discussion*

Luminous output peaks at 9.5 A before the increase in light output decreases. At this point with a combined LED output power of 27 W, a luminous output of 748 lm was measured, providing a luminous efficiency of 27.7 lm/W. Raising the LED current beyond 9.5 A resulted in a reduction in output, which combined with an increase in CCT and a stable LED temperature seen by the onboard thermistor also seen suggests a possible over-heating of the phosphor and a reduction in conversion efficiency. During the experiments, the etendue of the system is maintained through maintaining the aperture size of the LED through the system to the exit aperture and also the half acceptance angle through to the exit of the system. The total output and luminous efficiency are lower than predicted by the Zemax optical model, which were 3720 lm and 89 lm/W, respectively, and are to be accounted for by several factors. The Zemax model expects a perfect mechanical alignment between the edges of the glass pieces resulting in little loss. In reality, an ideal perfect alignment was not possible with some loss likely to have occurred between joints. Improvements could be possible through precisely machined assembly jigs or a less rigid material used for the substrate. As the spectral output shown in the Zemax model, Fig. 3(a) shows a relatively large broadband peak present from the phosphor emission. The output in practice is on the white light curve, as shown in Fig. 11 by the red cursor with a correlated color temperature of 12,000 K and a larger blue peak with a lower broadband yellow-green band, suggesting less blue light has been converted to the yellow-green emission of the phosphor.

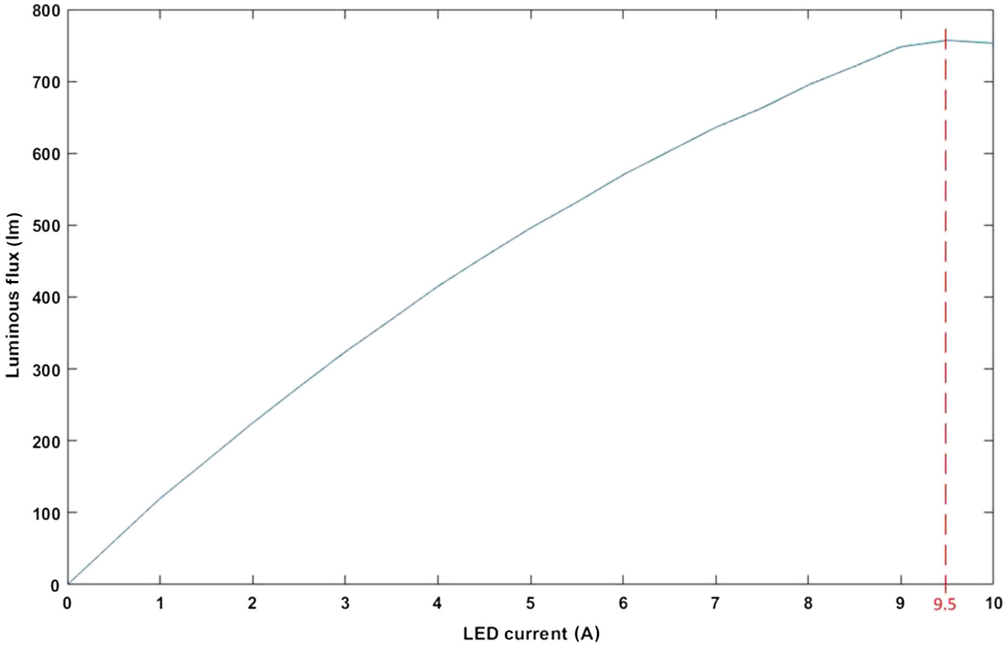


Fig. 12 Multi-pumped phosphor output luminous flux as a function of LED operating current.

Adjustments to the above setup would see an improvement in the total amount of light from the light guide as well as the efficiency. Addition of a cooling component for the light guide with a more thermally conductive substrate would reduce the chance of over-heating and possible thermal quenching of the phosphor and increase the maximum output. Increasing the area of phosphor coated onto the high-reflective glass inside the light guide would provide greater interaction and further conversion from blue to yellow-green light, increasing the luminous output and efficiency and creating greater opportunity to multiplex with additional blue and red light sources to increase total white light possibilities and combined with variations of phosphor coating, provide color tuning opportunities.

5 Conclusion

An etendue maintained white light optical source is realized by multi-pumping GAL (aluminate) green-yellow phosphor with three high-power Luminus Devices PT-121 LEDs. The three LEDs with identical optical characteristics are coupled into a high-reflective light guide system utilizing wavelength-dependent dichroic coated mirrors to excite the green-yellow phosphor, spun coated for uniform distribution. Etendue is maintained by keeping the output aperture identical to that of the input LEDs, increasing the collected light with the same emission geometry. LED stability is achieved with an active air-cooled system, to keep operating temperature below the maximum operating junction temperature. A system output of 750 lm is achieved with a white light CCT of 12,000 K. This is lower than the luminous output predicted Zemax optical model due to light lost through non-perfect hand built joining of optical components and thermal effects of the phosphor and throughput of non-converted blue light. Adjustments have been recognized to increase overall output within the high-luminosity yellow-green wavelength band to achieve an output closer to the predicted optical model. The system lends itself to color temperature tuning through varying amounts and positions of phosphor coated within the system as well as wavelength multiplexing with other wavelength sources. The maintained etendue of the system offers a suitable source for coupling to liquid light guides and other endoscopy equipment.

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