DETERMINING PHOSPHORS' EFFECTIVE QUANTUM EFFICIENCY FOR REMOTE PHOSPHOR TYPE OF LED MODULES

Arno Keppens[1,3,*], Yuqin Zong[2], Yoshi Ohno[2], G. Deconinck[3], and Peter Hanselaer[1,3]

[1] Light & Lighting Laboratory, Catholic University College Gent, Belgium

[2] National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA

[3] ESAT/ELECTA, K.U.Leuven, Belgium

ABSTRACT

Remote phosphor type light-emitting diodes (LEDs) are gaining popularity in all kinds of solid-state lighting applications. Main reasons are the high luminous efficiency in comparison with proximate phosphor type LED devices and the improved spatial color uniformity due to internal photon scattering.

Optical properties of a high-power white LED are highly dependent on the power and the temperature of the diode junction and phosphor. For a remote phosphor type LED module, junction and phosphor temperature can be very different. The effect of excitation light density, junction temperature, and ambient temperature on phosphor heating has therefore been studied. Results have been used to determine the effective quantum efficiency of remote phosphors as a function of phosphor temperature and pump light density.

Keywords: light-emitting diode, remote phosphor, phosphor temperature, effective quantum efficiency

1. INTRODUCTION

A lot of research is dedicated to determining the quantum efficiency (QE) of yellow phosphor powders for light-emitting diode applications, i.e. the number of converted photons relative to the number of absorbed blue pump photons [Narendran, 2005] [Winkler, 2007] [You, 2010]. The research however concentrates on measuring the phosphor apart from its final application in a remote phosphor type LED module. It is therefore appropriate to define effective quantum efficiency as the quantum efficiency of a phosphor plate when integrated in a lighting application. For the latter, all back-scattered photons are absorbed or redirected by the module, which may lead to remarkably different results in comparison with the QE measurement setup for the phosphor powder.

If the pump light spectrum shape does not significantly change, the remote phosphor's effective quantum efficiency will only depend on the phosphor temperature and excitation light density. The remote phosphor is thus first characterized by determining its temperature as a function of excitation light density, junction temperature, and ambient temperature. Afterwards, the effect of the phosphor temperature and excitation light density on effective quantum efficiency is examined.

2. EXPERIMENTS

The spectral radiant flux of a selection of three pump diode modules without phosphor plate has been determined for five forward currents (150 mA, 250 mA, 350 mA, 500 mA, and 700 mA) and five junction temperatures (25 °C, 40 °C, 60 °C, 80 °C, 100 °C) with a 1 m ambient-temperature-controlled integrating sphere connected to a CCD-array spectrometer with 3 nm bandpass. The same forward current and junction temperature settings were used during a second spectral radiant flux measurement series with the remote phosphor plates remounted on their respective pump devices (see Fig. 1). Combining the results of both series allowed calculating the effective quantum efficiency of the phosphors afterwards. The second measurement series has been repeated within three constant ambient sphere temperatures, being 25 °C, 40 °C, and 55 °C.

[*] This work has been performed while working as a Guest Researcher at NIST.

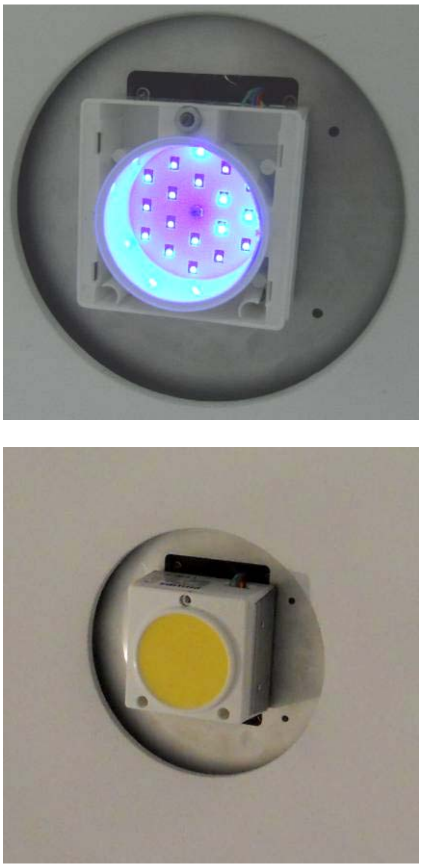

Figure 1. Remote phosphor type LED mounted on the sphere surface without (top) and with (bottom) its remote phosphor plate.

The junction temperature of each test LED was set by using a temperature-controlled heat sink mounted on the integrating sphere surface [Zong, 2008]. The phosphor temperature was recorded using a k-type thermistor connected with thermal paste.

3. RESULTS

3.1. Phosphor temperature

The remote phosphor of each device under test – named LED1 to LED3 – is first characterized by determining the phosphor temperature as a function of excitation light density, junction temperature, and ambient temperature. The excitation light density and junction temperature dependence have first been translated into a variation of the phosphor temperature with the diode forward current and board temperature. Experimental results of these variations determined within three different ambient sphere temperatures have been collected in Fig. 2.

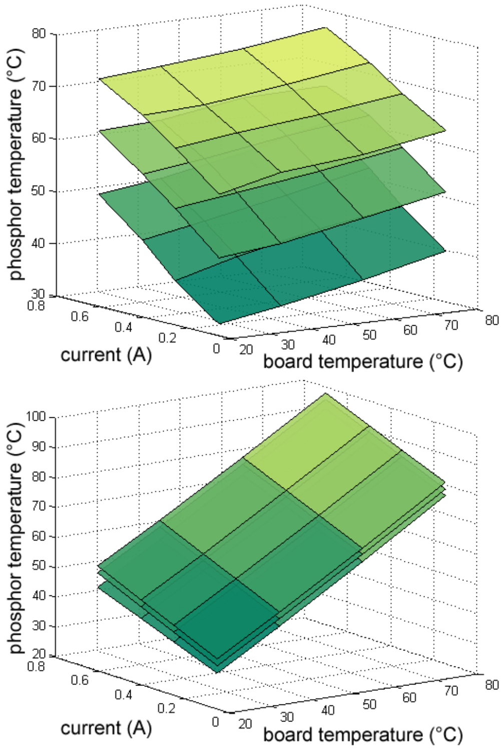

Figure 2. Phosphor temperature of LED1 (top) and LED3 (bottom) as a function of the forward current and board temperature for 25 °C, 40 °C, and 55 °C ambient sphere temperatures.

From Fig. 2, it is clear that the effect of an increasing current or pump flux is larger than the effect of an increasing board or junction temperature for LED1. This is due to the proportionality of phosphor heating with the number of absorbed pump photons, while the connection between junction and phosphor has a high thermal resistance for this device type. As a result, the ambient temperature largely influences the phosphor temperature. Indeed, the 15 °C ambient temperature increases result in phosphor temperature augmentations of about 10 °C for each setting of forward current and board temperature.

On the other hand, the junction-to-phosphor thermal resistance is lowest for LED3, which can be seen from the effect of ambient temperature on phosphor temperature for this device in Fig. 2. For each setting of the forward current and board temperature, the subsequent 15 °C ambient sphere temperature increases result in 2 °C to 3 °C phosphor temperature increases only. Consequently, a junction or board temperature variation has a much larger effect on the phosphor temperature than for LED1, while the dependence on forward current is slightly reduced. This corresponds with what can be expected.

The data described above show that pump chip(s) and phosphor have to be regarded as separate heat sources for remote phosphor type LEDs. The effect of ambient temperature variations on the phosphor temperature largely depends on the thermal resistance between those heat sources.

3.2. Effective quantum efficiency

The phosphors' effective quantum efficiency η_{eff} has been calculated as the number of converted photons relative to the number of absorbed blue pump photons. The converted photons are those in the fluorescence spectrum only, while the number of absorbed photons equals the difference of blue pump photons for the measurement without and with phosphor plate, respectively. As in each spectrum the total number of photons per wavelength λ equals $\Phi_{e,\lambda}\lambda/hc$, η_{eff} can be expressed as follows:

$$\eta_{\text{eff}} = \frac{\int \Phi_{e,\lambda,\text{conv}} \lambda d\lambda}{\int \Phi_{e,\lambda,\text{init}} \lambda d\lambda - \int \Phi_{e,\lambda,\text{trans}} \lambda d\lambda} \quad (1)$$

with $\Phi_{e,\lambda,\text{conv}}$, $\Phi_{e,\lambda,\text{init}}$ and $\Phi_{e,\lambda,\text{trans}}$ the phosphor-converted flux spectrum, initial pump flux spectrum and transmitted pump flux spectrum, respectively. Integrals go from 380 nm to 780 nm wavelengths.

Effective quantum efficiency values at 350 mA for a 60 °C junction temperature and a 25 °C ambient have been collected in Table 1 below. Corresponding phosphor temperatures and excitation fluxes have been added as well. Fig. 3 depicts the effective QE for LED2 as a function of phosphor temperature and pump flux.

Table 1. Phosphor temperature, pump flux, and effective QE at 350 mA for a 60 °C junction temperature and 25 °C ambient.

	LED1	LED2	LED3
phosphor temp (°C)	37.0	44.1	34.5
pump flux (W)	5.820	2.319	4.179
effective QE (%)	77.8	37.6	52.0

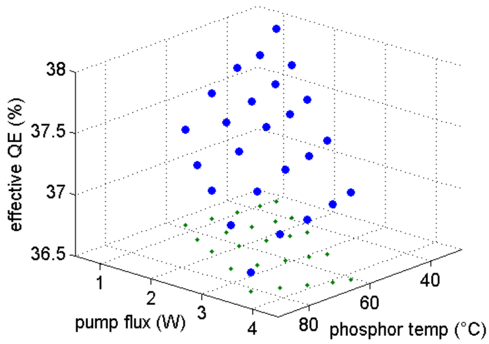

Figure 3. Effective QE for LED2 as a function of phosphor temperature and initial pump flux (large blue dots) and its projection in the horizontal plane (small green dots).

The steady-state effective quantum efficiencies in Table 1 roughly correspond with values reported in literature, but differ from efficiency values determined for non-integrated phosphors powders [Winkler, 2007] [Allen, 2008] [Hoelen, 2008]. Moreover, Fig. 3 shows that the effective quantum efficiency decreases with increasing phosphor temperature (about 0.03 %/K) and excitation light density (about 0.1 %/W). Within typical diode operation ranges, the pump flux effect is however negligible in comparison with the effect of temperature. Analogous results have been found for all devices under test. They correspond with typical phosphor powder efficiency behaviours that have been reported in literature [Zhang, 2008] [Setlur, 2009].

4. CONCLUSIONS

The phosphor temperature of a remote phosphor type LED module increases with increasing pump light flux and temperature of junction and ambient. This effect strongly depends on the phosphor's quantum efficiency and thermal resistance to the junction.

The effective quantum efficiency of three LED modules has been calculated from spectral radiant flux measurements with and without the respective remote phosphor plates. The experimental results correspond with values reported in literature, but differ from QE values determined for phosphors powders. Within typical diode operation ranges, the effective quantum efficiency decrease with pump flux (about 0.1 %/W) is negligible in comparison with the effect of an increasing phosphor temperature (about 0.03 %/K).

REFERENCES

Allen SC, Steckl AJ (2008). A nearly ideal phosphor-converted white light-emitting diode. *Appl. Phys. Lett.* **92**, 143309, 1-3

Hoelen C, Borel H, de Graaf J, Keupre M, Lankhorst M, Mutter C, Waumans L, Wegh R (2008). Remote phosphor LED modules for general illumination – towards 200 lm/W general lighting LED light sources. *Proc. SPIE* **7058**, 70580M, 1-10

Narendran N, Gu Y, Freyssinier-Nova JP, Zhu Y (2005). Extracting phosphor-scattered photons to improve white LED efficiency. *Phys. Stat. Sol. (a)* **202**, 6, R60-R62

Setlur AA, Shiang JJ, Hannah ME, Happek U (2009). Phosphor quenching in LED packages: measurements, mechanisms, and paths forward. *Proc. SPIE* **7422**, 74220E, 1-8

Winkler H, Enderle H, Kuehn C, Petry R, Vosgroene T (2007). Advanced phosphors for LED applications. *Proc. SPIE* **6797**, 67970A, 1-12

You JP, Tran NT, Shi FG (2010). Light extraction enhanced white light-emitting diodes with multi-layered phosphor-configuration. *Opt. Express* **18**, 5, 5055-5060

Zhang Y, Li L, Zhang X, Xi Q (2008). Temperature effects on photoluminescence of YAG:Ce3+ phosphor and performance in white light-emitting diodes. *J. Rare Earths* **26**, *3*, 446-449

Zong Y, Ohno Y (2008). New practical method for measurement of high-power LEDs. In CIE x033:2008, *Proc. CIE Expert Symposium on Advances in Photometry and Colorimetry*, 102-106

ACKNOWLEDGEMENTS

The authors would like to thank the National Institute of Standards and Technology (Gaithersburg, MD, USA) and the Belgian divisions of EREA, Massive (Network Philips Consumer Luminaires), R-Tech (Schréder group), and Sylvania.

AUTHORS

A. Keppens
Light & Lighting Laboratory
Gebroeders Desmetstraat 1
9000 Gent, Belgium
Phone +32 92 65 87 13
arno.keppens@kahosl.be

Y. Zong
NIST
100 Bureau Drive,
8442, Gaithersburg, MD, USA
Phone +1 301 975-2321
yuqin.zong@nist.gov

Y. Ohno
NIST
100 Bureau Drive
8442, Gaithersburg, MD, USA
Phone +1 301 975-2321
ohno@nist.gov

G. Deconinck
ESAT/ELECTA
Kasteelpark Arenberg 10,
3001 Leuven, Belgium
Phone +32 16 32 11 26
geert.deconinck@esat.kuleuven.be

P. Hanselaer
Light & Lighting Laboratory
Gebroeders Desmetstraat 1
9000 Gent, Belgium
Phone +32 92 65 87 13
peter.hanselaer@kahosl.be