Paper

Efficiency evaluation of phosphor-white high-power light-emitting diodes

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ABSTRACT

High-power light-emitting diode (LED) efficiencies are strongly dependent on device type and operating conditions. Electrical and optical power measurements are performed on five commercially available phosphor-white LED types for a number of independently enforced forward currents and junction temperatures. The experimental results allow for a comparative evaluation of dominant loss mechanisms and their current and temperature dependences.

KEYWORDS: phosphor-white LED, efficiency, loss mechanisms, current, junction temperature

1. Introduction

Light-emitting diodes (LEDs) have become very popular and certainly have proven their usefulness in a wide variety of applications. These include applications requiring narrow-band colour spectra [1) 2)] and indicative, decorative and signal lighting [3)]. It cannot be denied that especially the high-power LED technology is developing very quickly and may be considered a promising alternative for general lighting applications as well [4)]. Next to important efficiency improvements, the total luminous flux per device is increasing by combining different dies into one package and by allowing larger drive currents [5)]. However, the real breakthrough of LEDs in general lighting is still subject of discussion. Main obstacles are the moderate total system efficiency and luminous flux, the need for narrow colour binning regions when combining several devices, and the production price [5) 6) 7)]. Furthermore, optical and electrical characteristics strongly depend on the diode junction temperature, which in turn is determined by the forward current, heat sink size and ambient temperature [8)]. Low junction temperatures are especially favourable regarding flux, efficiency and lifetime, while high temperature operation strongly reduces the overall diode performance [9) 10) 11) 12)]. Additionally, the present lack of international standardization regarding the optical and electrical characterization of LEDs is compromising a successful implementation.

Numbers quoted for (luminous) flux, and consequently for efficiency of LEDs, are very sensitive data as they are used to impress and push the LED market. Nowadays, specification data can be misleading as the measurement conditions are often not well defined. Efficiency measurements and output comparison, including the current and temperature dependence of the results, are therefore of major importance in current high-power light-emitting diode research [10)]. In literature however, often only very specific efficiency measurements are discussed, e.g. the diode extraction efficiency [13)] or luminous efficacy [14)]. Recently, there is a trend towards more combined efficiency determination. Examples of the latter are [7) 10) 15)]. Nevertheless, none of these publications has the intention to unite a maximum number of efficiency measurements in one setup, which allows connecting power and loss calculations by use of the energy conservation relation. Such extended efficiency study with current and temperature dependences is performed in this work.

2. Experiments

Five commercial phosphor-white high-power LED packages, indicated L1 to L5, have been selected for investigation through various current-voltage and spectral radiant flux measurements.

Forward current-voltage characteristics at different junction temperatures have been determined by placing the LEDs in a Heraeus UT6 isothermal oven with active air circulation [16]. The predefined oven temperatures (300, 320, 340, and 360 K) have been precisely measured with a PT100 thermistor. In order to avoid junction heating during measurement, a Keithley 2440 5A SourceMeter was pulse-operated by a LabVIEW program (single 1 μs pulses).

Spectral radiant flux and input power measurements at different currents and junction temperatures have been performed with a custom-made integrating sphere [17]. The LEDs were attached to the sphere surface using an aluminium mounting plate incorporating a Peltier element and PT100 thermistor (see Figure 1). The Peltier element regulates the plate temperature until the LED junction temperature – determined by forward voltage measurement [16] – shows the desired value.

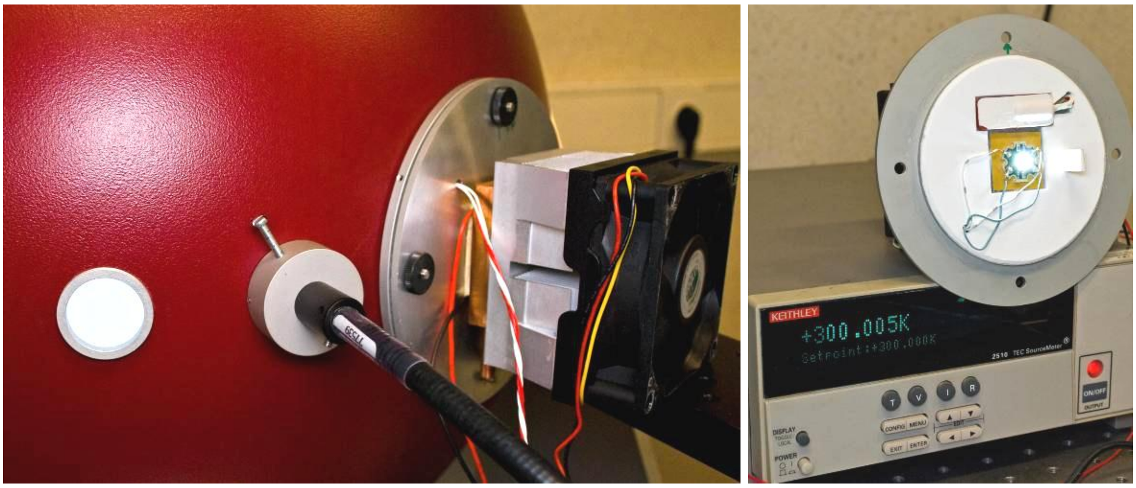

Figure 1 Integrating sphere (left) with reference port, detector port, and sample port, respectively. The sample is temperature controlled using a Peltier element. On the front side of the sample port plug the high-power diode package, a PT100 thermistor and a small baffle are mounted (right).

3. Efficiency scheme

An overview of all power losses in a general LED application can be found in Figure 2. For vocabulary and notations CIE guidelines have been followed as much as possible [18].

In Figure 2, P_1 corresponds to the total input power from the grid. The subsequent power losses within a LED application are due to the following phenomena:

- Power conversion in the driver electronics (loss ΔP_1).
- Voltage drops in the wiring, the current spreading layer and (neutral regions in) the bulk semiconductor [19], and voltage drops due to charge carrier relaxation in quantum wells by phonon emission [20]. These losses can approximately be considered as voltage drops due to an overall internal series resistance (ΔP_2). These losses are however not only dissipated into the bulk or the diode junction.
- Non-radiative recombinations, such as Auger recombination or phonon creation near defects in the crystal structure or at surface dangling bonds (ΔP_3) [20] [21].
- Refractive index differences between diode chip and packaging on the one hand, and between packaging and air on the other, cause important photon absorption. Secondly, there is a chance that a photon travelling in the bulk of the device is absorbed in the cladding layers or in the current spreading window. Next to that, some photons can be absorbed in the active region, producing electron-hole pairs which afterwards recombine non-radiatively. Finally, since contacts are not very good reflectors, they decrease the photon extraction efficiency as well [13]. These losses are combined in ΔP_4 and ΔP_5.
- Analogous photon extraction efficiency can be defined for the wavelength-converting phosphor, often referred to as quantum yield. For remote phosphors, this efficiency $\Delta P_{ext,phos}$ can be determined separately [22]. The phosphor layer and its corresponding losses are missing for single-colour LEDs.

- Wavelength conversion in the phosphor – the Stokes shift – decreases the wavelength of an incoming pump photon, resulting in a photon energy loss ΔP_S [20]. This energy is absorbed by the phosphor, thus increasing its temperature.
- Secondary optics, including additional reflectors or lenses constructing a complete luminaire (ΔP_6).
- The radiometric light output Φ_e will be visible for the human eye according to the spectral luminous efficiency $V(\lambda)$ [18]. This phenomenon is referred to as the eye sensitivity and corresponding loss ΔP_{vis}, and has nothing to do with heat dissipation into the diode package.

In practice, all power and efficiency values are current and junction temperature dependent. These dependencies will be included in the following sections. This work only concentrates on commercial LED packages, meaning that driver electronics and secondary optics are no longer taken into account.

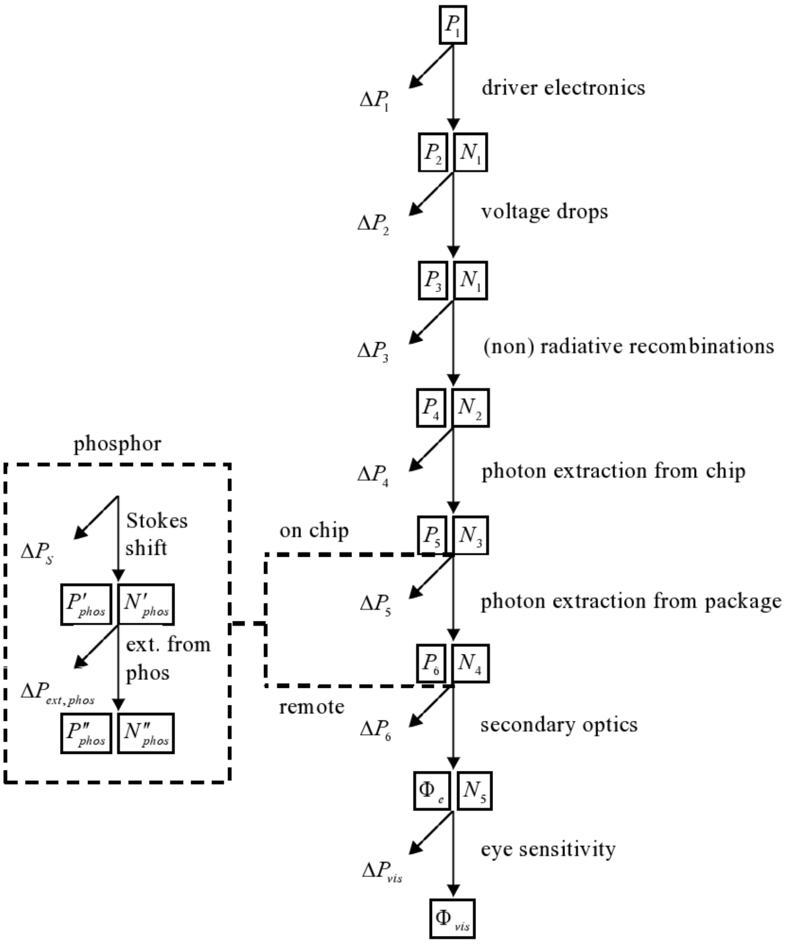

Figure 2 Overview of power and particle losses in a general LED application.

4. Calculations

For every step $s \rightarrow s+1$ in the efficiency scheme, the following equation is valid:

$$P_{s+1} = P_s - \Delta P_s \quad (1)$$

with P_s the useful power left at stage s and ΔP_s the power lost during the transition $s \rightarrow s+1$. Taking into account the energy conservation relation, one can therefore write for the complete scheme:

$$P_t = \Phi_{vis} + \sum_s \Delta P_s \quad (2)$$

with P_t the total input power (P_1 in Figure 2). Similar relations can be constructed for the respective numbers of particles N_s (electrons or photons). The corresponding efficiency η_s of each step $s \rightarrow s+1$ is defined by:

$$\eta_s = \frac{P_{s+1}}{P_s} \quad (3)$$

resulting in a total efficiency η_t given by:

$$\eta_t = \prod_s \eta_s \tag{4}$$

The power loss ΔP_s can be calculated from the efficiency corresponding to the transition $s \rightarrow s+1$ and the resulting power P_{s+1} only. Combination of Eqs. (1) and (3) yields:

$$\Delta P_s = P_{s+1}\left(\eta_s^{-1} - 1\right) \tag{5}$$

According to Eq. (2), the package input power P can be written as:

$$P = \Delta P_R + \Delta P_{EQ} + \Delta P_{vis} + \Phi_{vis} \tag{6}$$

This equation is valid for single-colour LEDs. The power loss into the internal series resistance, eye sensitivity loss and visible flux are denoted as ΔP_R, ΔP_{vis} and Φ_{vis}, respectively. Power losses due to non-radiative recombinations and due to photon absorption in chip and package are combined into a single term ΔP_{EQ} which is related to the total external quantum efficiency of the device.

For phosphor-white LEDs Eq. (6) becomes:

$$P = \Delta P_R + \Delta P_{EQ} + \Delta P_S + \Delta P_{vis} + \Phi_{vis} \tag{7}$$

where an extra power loss into the phosphor due to the Stokes shift ΔP_S is included. The phosphor's extraction efficiency is added to the total external quantum loss ΔP_{EQ}. All power losses on the right hand side of Eq. (7) are visualised in Figure 3.

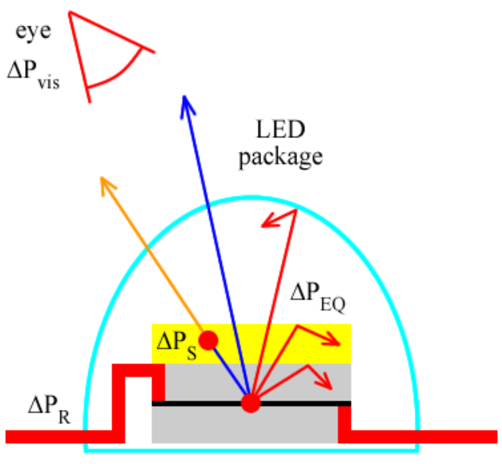

Figure 3 Visualisation of power losses for a phosphor-white LED package. The flux has a pump contribution (right outgoing arrow in blue) and a proximate phosphor contribution (left outgoing arrow in yellow).

The current (I) and temperature (T) dependent input power and power loss into the internal series resistance R_S are given by:

$$P(I,T) = IU_f(I,T) \tag{8}$$

and

$$\Delta P_R(I,T) = I^2 R_S(T) \tag{9}$$

respectively, if U_f denotes the diode forward voltage. $R_S(T)$ is determined from current-voltage characteristics [23]. The efficiency related to the internal series resistance η_R can then be calculated as:

$$\eta_R(I,T) = 1 - \frac{IR_S(T)}{U_f(I,T)} \tag{10}$$

The overall external quantum efficiency $\eta_{EQ}(I,T)$ is calculated as the number of emitted photons divided by the number of injected electrons (with wavelengths λ in nm) [18]:

$$\eta_{EQ}(I,T) = \frac{\int_{380}^{780} \Phi_{e,\lambda}(I,T)\frac{\lambda}{hc}\,d\lambda}{I/e} \tag{11}$$

$\Phi_{e,\lambda}$, h, c, and e represent the spectral radiant flux, Planck constant, speed of light in vacuum and electron charge, respectively. Assuming that the energy of each photon created in the junction (hc/λ) on average equals the electron energy loss associated with the applied forward voltage, the quantum efficiency related to particle numbers in Eq. (11) can be considered valid for the corresponding energy values as well [20]. By use of Eq. (5), the power loss resulting from this external quantum efficiency becomes:

$$\Delta P_{EQ}(I,T) = \frac{\Phi_{e,pump}(I,T)}{f_{pump}(I,T)}\left[\frac{1}{\eta_{EQ}(I,T)} - 1\right] \tag{12}$$

with $\Phi_{e,pump}$ the measured pump spectrum and f_{pump} the pump light leakage fraction:

$$f_{pump}(I,T) = \frac{\int_{380}^{780} \Phi_{e,\lambda,pump}(I,T)\lambda\,d\lambda}{\int_{380}^{780} \Phi_{e,\lambda}(I,T)\lambda\,d\lambda} \tag{13}$$

i.e. the number of photons emitted by the pump divided by the total number of emitted photons [10]. This fraction equals one for single-colour LEDs. In that case $\Phi_{e,pump}$ is replaced by the total radiant flux Φ_e in Eq. (12) as well. For all diode types $\Phi_{e,pump}/f_{pump}$ thus equals the power of all photons in the flux spectrum before potential phosphor conversion.

Radiant fluxes are determined as:

$$\Phi_e(I,T) = \int_{380}^{780} \Phi_{e,\lambda}(I,T)\,d\lambda \qquad (14)$$

The efficiency of the Stokes shift is generally approximated by the ratio of the average phosphor photon energy E_{phos} and pump photon energy E_{pump} [20]:

$$\eta_S(I,T) \approx \frac{E_{phos}}{E_{pump}} = \frac{\lambda_{pump}}{\lambda_{phos}} \qquad (15)$$

Again using Eq. (5), this corresponds to a Stokes power loss:

$$\Delta P_S(I,T) \approx \Phi_{e,phos}(I,T)\left(\frac{\lambda_{phos}}{\lambda_{pump}} - 1\right) \qquad (16)$$

with $\Phi_{e,phos}$ and λ_{phos} the measured fluorescence spectrum and its peak wavelength, respectively. λ_{pump} stands for the measured pump wavelength.

Taking into account the rather wide phosphor spectrum and the small blue spectrum, the power loss into the phosphor due to the Stokes shift can be calculated more accurately by totalling the power losses of all phosphor wavelengths:

$$\Delta P_S(I,T) \approx \int_{380}^{780} \Phi_{e,\lambda,phos}(I,T)\left(\frac{\lambda}{\lambda_{pump}} - 1\right)d\lambda \qquad (17)$$

The Stokes efficiency $\eta_S(I,T)$ then becomes:

$$\eta_S(I,T) \approx \frac{\int_{380}^{780} \Phi_{e,\lambda,phos}(I,T)\,\lambda_{pump}\,d\lambda}{\int_{380}^{780} \Phi_{e,\lambda,phos}(I,T)\,\lambda\,d\lambda} \qquad (18)$$

The visible flux is determined by inserting the spectral luminous efficiency $V(\lambda)$ into Eq. (14):

$$\Phi_{vis}(I,T) = \int_{380}^{780} \Phi_{e,\lambda}(I,T)V(\lambda)\,d\lambda \qquad (19)$$

The eye sensitivity loss ΔP_{vis} thus equals:

$$\Delta P_{vis}(I,T) = \int_{380}^{780} \Phi_{e,\lambda}(I,T)\left[1 - V(\lambda)\right]d\lambda \qquad (20)$$

Eq. (19) shows that the visible flux also equals the luminous flux Φ_v divided by the maximum luminous efficacy of radiation K_m = 683 lm/W. Indeed, Φ_v is defined by:

$$\Phi_v(I,T) = K_m \int_{380}^{780} \Phi_{e,\lambda}(I,T)V(\lambda)\,d\lambda \qquad (21)$$

The visibility efficiency η_{vis} equals:

$$\eta_{vis} = \frac{\Phi_{vis}}{\Phi_e} = \frac{K}{K_m} \qquad (22)$$

by combining Eqs. (19) and (21), and with K the total luminous efficacy of radiation:

$$K(I,T) = \frac{\Phi_v(I,T)}{\Phi_e(I,T)} \qquad (23)$$

For completeness, also the full efficiency equation for phosphor-white LEDs is constructed. The efficiency and luminous efficacy of a complete LED package are defined as:

$$\eta_e(I,T) = \frac{\Phi_e(I,T)}{P(I,T)} \qquad (24)$$

and

$$\eta_v(I,T) = \frac{\Phi_v(I,T)}{P(I,T)} \qquad (25)$$

respectively, meaning that $\eta_v = \eta_e K$. In correspondence with Eq. (4), Eqs. (10), (11), (18), (22), (23), and (25) can therefore be combined to the following formula, adapted from [10]:

$$\eta_v = \eta_R\ \eta_{EQ}\left[f_{pump} + \left(1 - f_{pump}\right)\eta_S\right]\eta_{vis}\ K_m \qquad (26)$$

For $f_{pump} = 1$ the Stokes efficiency drops out and Eq. (26) becomes the efficiency equation for a single-colour LED.

5. Results and discussion

For all five phosphor-white LED devices under test, each power loss in Eq. (7) has been calculated by use of Eqs. (8) to (21). Only the spectral radiant flux and forward voltage at a given diode current and junction temperature are required as input parameters (see section 2). Measurements have however been performed for a range of forward current values (100, 175, 250, 350, and 500 mA) and junction temperature values (about 290, 300, 315, 330, and 340 K). The resulting data matrix allows examining the current and junction temperature dependence of all power losses discussed above. These dependences have been studied in detail for a constant 300 K junction temperature and a constant 350 mA drive current, respectively. Results are visualized for LED L1 in Figure 4.

The results in Figure 4 (top) show that with increasing current, the quantum losses ΔP_{EQ} , Stokes losses ΔP_S , and visual losses ΔP_{vis} increase quasi linearly. This suggests that the quadratic increase of the power loss into the internal series resistance ΔP_R (see Eq. (9)) forms the main reason for the decreasing diode efficiency with increasing current.

On the other hand, Figure 4 (bottom) shows that the decreasing overall diode efficiency with junction temperature is only due to the increasing external quantum loss ΔP_{EQ} with increasing temperature, as other losses slightly decrease. Similar results are found for all LED packages under consideration.

The four power loss terms and remaining visible flux on the right-hand side of Eq. (7) have also been mutually compared for all devices under test at normal operating conditions, i.e. 350 mA forward current and 330 K junction temperature. Results are represented in a bar plot in Figure 5. Dividing each loss term and the visible flux by the total input power for each diode normalizes the scale.

Rather surprisingly, the data in Figure 5 shows that the internal series resistance directly consumes about 10 to 20 % of the initial input power. As a result, the overall efficiency can be remarkably higher for LEDs with a reduced resistance (e.g. L1).

External quantum loss ΔP_{EQ} is clearly the dominant loss factor and can be related to the colour temperature of the LEDs. Indeed, L1 and L2 are cool white devices (6000 K) and exhibit the smallest quantum losses. L3 is neutral white (4500 K), while L4 and L5 are warm white (3000 K). Non-fluorescent absorption in the phosphor seems to be more important for these warm white LEDs. For this reason, the package efficiency is always higher for cool white LEDs [20].

The Stokes shift losses ΔP_R equal about 2 to 5 % of the total input power for all measured LEDs. Although the Stokes shift (conversion loss per photon) is larger for warm white LEDs, this effect seems to be compensated by the smaller number of emitted photons. The remaining visible flux part is always just a few percent smaller than the visual loss for phosphor-white LED spectra.

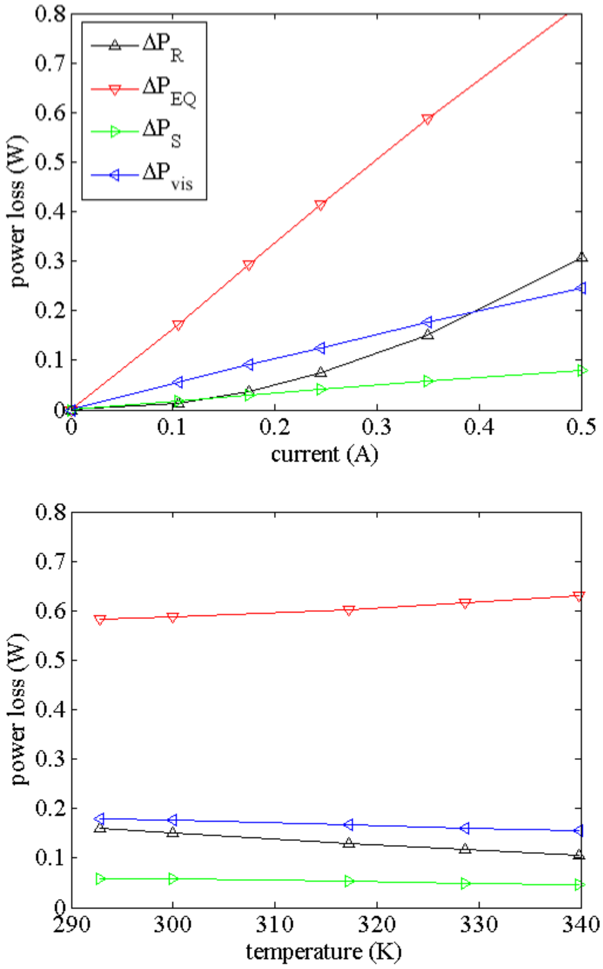

Figure 4 Power losses as a function of current at 300 K (top), and as a function of junction temperature at 350 mA (bottom) for LED L1.

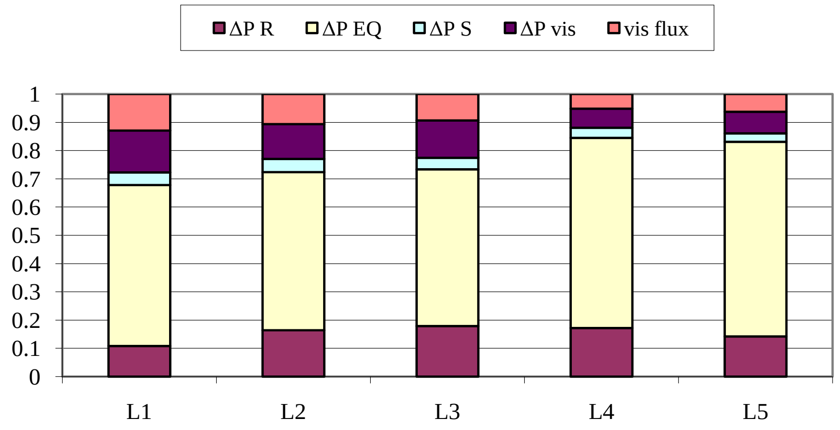

Figure 5 Comparison of normalised power losses and visible flux for five LEDs at 350 mA and 330 K (colours from left to right in legend correspond with colours from bottom to top in graph).

6. Conclusions

Several power loss mechanisms present in phosphor-white high-power LEDs are calculated and evaluated for different operating conditions and mutually compared. Power loss in the internal series resistance has been found to amount 10 to 20 % of the initial input power and is the main reason for the decreasing diode efficiency with increasing current. External quantum losses are clearly the dominant loss factor and can be related to the colour temperature of the LEDs. Non-fluorescent absorption in the phosphor seems to be more important for warm white LEDs. The external quantum losses are also responsible for the efficiency decrease with junction temperature. For this reason, the LED efficiency is always higher for cool white LEDs. The Stokes shift losses equal about 2 to 5 % of the input power for all measured LEDs. Although the conversion loss per photon is larger for warm white LEDs, this effect seems to be compensated by the smaller number of emitted photons. The remaining visible flux part is always a few percent smaller than the visual loss for phosphor-white LED spectra.

7. Acknowledgements

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