RELATIONSHIPS BETWEEN JUNCTION TEMPERATURE, FORWARD VOLTAGE AND SPECTRUM OF LEDs

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Motivation

• Lifetime of an LED is affected by its junction temperature
• In assembled luminaires junction temperature is inaccessible
• Junction temperature affects the LED spectrum
  – Could temperature be derived by measuring LED spectrum?
  – Does spectrum of a multi-LED lamp tell us something about the temperatures of the individual LEDs?
Research carried out

1. Five types of LED lamps were disassembled resulting in 1 blue, 1 red and 4 white LEDs to be studied
2. Electrical calibration of relationships between $I$, $U$ and junction temperature $T_j$ (forward voltage method)
3. Spectra measured as functions of $T_j$
4. Model based on Maxwell-Boltzmann distribution studied and applied
5. Tests and considerations with lamp spectra
Measurement of LED spectra at various $T_j$

• LEDs extracted were set at varied temperatures using an oil bath
• Current – forward voltage characteristics measured with short current pulses
• LEDs set at known temperatures and spectra measured
→ Spectra in the temperature range 30 – 150 °C (303 – 423 K)
Forward voltage method

- Forward voltages of LEDs as function of temperature at varied current levels
- Unknown temperature can be obtained from measured electrical parameters
- Uncertainties:
  - Temperature ± 0.2 K
  - Voltage ± 2 mV
  - Current ± 0.5 mA

<table>
<thead>
<tr>
<th>O_A40-B</th>
<th>current (mA)</th>
<th>30°C</th>
<th>50°C</th>
<th>100°C</th>
<th>150°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>3,447</td>
<td>3,389</td>
<td>3,294</td>
<td>3,210</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>3,636</td>
<td>3,571</td>
<td>3,467</td>
<td>3,382</td>
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</tr>
<tr>
<td>790</td>
<td>3,791</td>
<td>3,720</td>
<td>3,610</td>
<td>3,525</td>
<td></td>
</tr>
<tr>
<td>840</td>
<td>3,826</td>
<td>3,755</td>
<td>3,643</td>
<td>3,558</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>4,077</td>
<td>3,998</td>
<td>3,875</td>
<td>3,789</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Cabling for Osram Parathom Classic A40.
Spectra at varied temperatures

- Operated with DC
- Temperatures varied over 30 – 150 °C (303 – 423 K)
- CS-1000 spectroradiometer and integrating sphere used for spectral measurement
- Spectral changes:
  - Wavelength shift
  - High energy slope of the blue peak
Modeling the LED spectrum

- The high energy side of (red) LED spectrum follows Maxwell-Boltzmann distribution

\[ R(E)dE = CE \Re \left\{ \sqrt{E - E_g} \right\} e^{-\frac{E}{k_BT_c}} dE \]

- Inverse derivative temperature \((T_{ID})\) and Characteristic temperature \((T_c)\) :

\[ T_{ID} = -\frac{1}{k_B \theta_{slope}} \quad T_c = \frac{\Delta}{k_B} \left[ \sqrt{1 + \frac{2k_BT_{ID}(\Delta)}{\Delta}} - 1 \right] \]

- For red LEDs \(T_j \approx T_c\) (Within couple of K)
- For blue and white LEDs, \(MB\)-distribution is not accurate -> Calibration needed
Practical method for calibrating blue and white LEDs

- For red LEDs, $T_c$ is applicable and gives reasonably accurate $T_j$:
- With blue and white LEDs, $T_{ID}$:s are derived in the intensity region 1% - 70% from spectra with known $T_j$:s
- Linear equations $T_j = a T_{ID} + b$ fitted to obtain slope and offset parameters
- Effects of current and inter-specimen variations considered
Example: Temperature of a blue LED

- Blue Philips Masterled spectra measured at various junction temperatures
- $T_{ID}$'s derived from the slopes in region 1% - 70% (black curves)
- Linear dependence between $T_j$ and $T_{ID}$
- Slope term is rather constant $T_j / T_{ID} = 0.804 \pm 0.038$
- Offset term varies between -21 and -116 K
- One calibration measurement needed for each LED specimen
Summary of other lamps

- slope term typically constant within 5 – 8 %.
- If LED specimens are calibrated with one measurement, e.g. in room temperature, temperature at 100 °C may be obtained with ~5 K uncertainty using average slope.
Effect of current on $T_j - T_{ID}$ curves

- With the blue (left) and the red LEDs, the effect of current on the slope was less than 2%.
- With white LEDs (right), increasing the current changed the slope systematically by 5%, indicating probably nonlinear behavior of the phosphor coating.
LED lamps: Inter-specimen variations

• Lamp bulbs removed
  – Lamps screened to measure spectra of individual LEDs
  – Unscreened lamp measured as well
  – Bulb transmittances measured

• $T_{ID}$ and $T_{C}$ calculated for all combinations
  – The standard deviations of the temperatures for individual LEDs range between 0.8–4.4 % (16 K@100 °C)
  – The deviations of the apparent $T_{ID}$:s for the lamp spectra deviated 7 K – 16 K from the average temperatures of the LEDs
  – Deviations in the earlier results were higher, most likely due to uncertainty of the forward voltage method

<table>
<thead>
<tr>
<th>Temperature</th>
<th>LED 1</th>
<th>LED 2</th>
<th>LED 3</th>
<th>LED 4</th>
<th>LED 5</th>
<th>LED 6</th>
<th>LED average</th>
<th>Standard deviation</th>
<th>LED sum</th>
<th>Lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tid</td>
<td>629</td>
<td>634</td>
<td>639</td>
<td>640</td>
<td>635</td>
<td>643</td>
<td>637</td>
<td>5</td>
<td>643</td>
<td>629</td>
</tr>
<tr>
<td>Tc</td>
<td>525</td>
<td>531</td>
<td>535</td>
<td>533</td>
<td>532</td>
<td>538</td>
<td>532</td>
<td>4</td>
<td>545</td>
<td>530</td>
</tr>
</tbody>
</table>
LED lamps: effect of bulb

- Lamps were measured for spectral radiant flux in a sphere with both bulbs on and bulbs removed.
- Bulbs generally drop the radiometric temperatures due to absorption in blue.
- Work is underway to study whether correction could be derived from bulb transmittance.

### Inverse derivative temperatures / K

<table>
<thead>
<tr>
<th></th>
<th>Without bulb</th>
<th>With bulb</th>
<th>Effect of bulb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp 1</td>
<td>836</td>
<td>812</td>
<td>-2.9 %</td>
</tr>
<tr>
<td>Lamp 2</td>
<td>824</td>
<td>753</td>
<td>-8.6 %</td>
</tr>
<tr>
<td>Lamp 3</td>
<td>663</td>
<td>606</td>
<td>-8.6 %</td>
</tr>
<tr>
<td>Lamp 4</td>
<td>563</td>
<td>560</td>
<td>-0.5 %</td>
</tr>
<tr>
<td>Lamp 5 *)</td>
<td>507</td>
<td>604</td>
<td>19.1 %</td>
</tr>
</tbody>
</table>

*) Remote phosphor
Conclusions

• Inverse derivative temperature $T_{ID}$ can be calibrated to give junction temperatures $T_j$ for red, blue and white LEDs
  – Linear dependence: $T_j = a \ T_{ID} + b$
  – $a$ and $b$ depend on LED type
  – Parameter $a$ constant within 5 – 8 % for the LED types studied
  – Large variations upto 90 K of $b$ even within one LED type.

• Practical method for determining $T_j$
  – Each LED type measured to get relationship between $T_j$ and $T_{ID}$
  – In addition, one measurement is needed for each LED specimen
  – Uncertainty of 5 K obtainable

• Lamps contain various LEDs
  – Preliminary measurements indicate that the apparent $T_{ID}$ for a lamp follows the average of the temperatures of the individual LEDs
  – Lamp bulb generally drops the radiometrically determined temperature