The Issues of Measurement of Optical Hazard Using Photometers
EMRP JRP ENG05
Metrology for Solid State Lighting
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Background

- Increasing demand for optical radiation safety related testing
  Lamps (UV),
  LEDs (UV,VIS,NIR)

- Increasing concern with light safety
  European Union ‘AORD’ safety requirement
  LED product safety
  e.g. LED signalling
  Safety of LED lighting (Blue Light Hazard);
  Photobiological ‘manipulation’ using light
safety studies

- ANSES – France 25/10/201
  LED Lighting health issues

- SCENIHR – EU 19/3/2012
  EU Scientific Committee on Emerging and Newly Identified Health Risks

- CELMA – EU 09/2011
  European Lamp Companies Federation
  ‘Biological Efficient Illumination’

Adverse and beneficial impact of LED lighting is an important and newly emerging field
Underpinning Issues

- Two ‘core’ measurement parameters
  - Spectral irradiance
  - Spectral radiance

  …spectral irradiance using a defined ‘Field of View’

  *Note: ‘field of view’ ≅ ‘acceptance angle’*
Exposure Hazard Value (EHV)

Need to compare the exposure to the beam against defined permissible limits i.e. Quantify the Exposure Hazard Value (EHV)
Keynote Concern: EHV ± U?

- Optical safety testing requires:
  Effective EHV < 1.0 where:
  \[ \text{Effective EHV} = \text{EHV} \text{(meas)} - \text{EHV} \text{(Uncertainty)} \]

- What is the uncertainty in the reported EHV?
- How does EHV uncertainty depend on test parameters?
- How much conservatism should be adopted?

{Note: This paper does not include systematic reproducibility of testing setup.}
Optical Safety Hazard bands

Actinic UV  Near UV  Blue Light Hazard
<table>
<thead>
<tr>
<th>IEC 62471 Hazard Band</th>
<th>Wavelength Range (nm)</th>
<th>Measurement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinic UV Skin &amp; Eye</td>
<td>200 to 400</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Eye UV-A</td>
<td>315 to 400</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Blue Light ‘small’ source</td>
<td>300 to 700</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Blue Light ‘extended’ source</td>
<td>300 to 700</td>
<td>Radiance</td>
</tr>
<tr>
<td>Retinal Thermal</td>
<td>380 to 1400</td>
<td>Radiance</td>
</tr>
<tr>
<td>Retinal thermal (weak stimulus)</td>
<td>780 to 1400</td>
<td>Radiance</td>
</tr>
<tr>
<td>Infrared hazard to eye</td>
<td>780 to 3000</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Skin thermal hazard</td>
<td>380 to 3000</td>
<td>Irradiance</td>
</tr>
</tbody>
</table>

Retinal hazards based on a radiance assessment
Spectral Radiometry

Double monochromator method
Test methodologies

- Radiance & Irradiance testing regimes
Radiance Testing Basics

EyeLIGHT Software Platform

Metrology for Solid State Lighting

European Association of National Metrology Institutes
IEC 62471: - Practical Testing

LED lamps and luminaires

Practical LED Safety Testing

National Physical Laboratory
Centre for Carbon Measurement

Metrology for Solid State Lighting

European Association of National Metrology Institutes
Radiance Problem (LED Array Sources)
Radiance Dependencies

- Field Stop Diameter
- Aperture Stop Diameter
- Apparent Source Location (distance)
- Acceptance Angle
- Field of View
- Solid Angle
- Spectral Radiant Power
- Wavelength
Software Evaluation Method

- Select representative source spectrum
  - eg 440 nm indigo blue LED,
  - High brightness cool white LED,
  - Ultraviolet LED
- Adjust the source metrics to yield $EHV = 1.0$
  (see next page)
- Vary the source metrics
- Explore influence upon $EHV$ Value
- Relate to uncertainty level
‘Scaling the Metrics’

Indigo blue LED (440 nm)
Total spectral radiance \( L = 105 \text{ W.m}^{-2}\text{.sr}^{-1} \)
Blue Light Hazard EHV = 1.0
Influence of Spectral Properties

- Define the spectrum
- Slide through Hazard Band
- Plot EHV
Dynamic EHV Tracking

EHV Tracker

- FWHM 25 nm
- FWHM 50 nm
- FWHM 100 nm
EHV & Spectral Analysis - Outcome

- Wavelength offset modifies EHV value
  1% for every 10 nm shift
  Surprisingly low effect

- Spectral linewidth
  Increasing FWHM reduces EHV ‘finesse’
  2% EHV reduction per 5 nm broadening
Spectral Irradiance Measurement

\[ P_a = \eta \cdot P_0 \]

\( P_a \) = accessible emission at aperture
\( \eta \) = efficiency of collection condition
\( P_0 \) = total emission output

\[ d_{63} = \frac{1}{e} \text{ beam diameter} \]
\[ d_a = \text{ aperture diameter} \]

Irradiance = Power per unit detector area
Irradiance Coupling

- **Uniform Irradiance at Aperture Stop**
  Coupled power increases quadratically with stop diameter
  Calculated Irradiance is constant with stop size

- **Gaussian Profile Irradiance at Aperture Stop**
  Coupled power decreases exponentially with increasing stop diameter
  Irradiance falls with increasing stop size

- **IEC 62471-1 Recommendation**
  Use 7 mm diameter unless irradiance at detector has good uniformity profile
## EHV versus Detector Aperture Stop

<table>
<thead>
<tr>
<th>Beam Divergence</th>
<th>$d_{63}$ at 200 mm</th>
<th>Practical Stop Diameter</th>
<th>Gaussian Coupling Efficiency</th>
<th>Accessible Emission</th>
<th>EHV</th>
<th>Aperture Stop Irradiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>mrad</td>
<td>deg</td>
<td>mm</td>
<td>mm</td>
<td>%</td>
<td>uW</td>
<td>W.m$^{-2}$</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>20</td>
<td>6.9</td>
<td>11.2</td>
<td>30.8</td>
<td>0.97</td>
</tr>
<tr>
<td>20</td>
<td>7</td>
<td>6.9</td>
<td>11.5</td>
<td>31.7</td>
<td>1.00</td>
<td>0.82</td>
</tr>
<tr>
<td>20</td>
<td>7.1</td>
<td>11.8</td>
<td>32.5</td>
<td>1.02</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>29</td>
<td>102</td>
<td>6.9</td>
<td>0.457</td>
<td>30.8</td>
<td>0.97</td>
</tr>
<tr>
<td>102</td>
<td>7</td>
<td>0.470</td>
<td>31.7</td>
<td>1.00</td>
<td>0.82</td>
<td></td>
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<tr>
<td>102</td>
<td>7.1</td>
<td>0.483</td>
<td>32.6</td>
<td>1.03</td>
<td>0.84</td>
<td></td>
</tr>
</tbody>
</table>

*Typically 2-3% EHV change per 100 micron diameter uncertainty*
EHV versus Aperture Stop

- As aperture stop is increased
  Detected radiant power should increase

- EHV assessment calculation
  Assumes defined stop diameter
  e.g. 7.0 mm aperture stop at 200 mm distance

- Use of slightly large aperture stop setting
  Will overestimate EHV result
  Typically 2-3 % EHV increase for gaussian profile
  beam at stop set incorrectly by + 100 $\mu$m

Yields a conservative EHV outcome
Spatially Averaged Radiance

Radiance = Detected Irradiance per unit source solid angle
Exempt & Low Risk BLH

- Blue Light Hazard Testing – Exempt Condition
  Exposure Time = 10000 s
  Acceptance Angle $\gamma = 100$ mrad (‘field of view’)
  Implies a 20 mm diameter field stop located over the source

- Blue Light Hazard Testing – Low Risk Condition
  Exposure Time = 100 s
  Acceptance Angle $\gamma = 11\text{mrad}$
  Implies a 2.2 mm diameter field stop located over the source

Field stop setting precision will influence radiance result

Reference Test Method recommends ‘imaging’ setup
Low Risk BLH Imaging Method

Source 1:1 imaging lens Field of View
Low Risk BLH Imaging Method

Field stop and LED chip size are both of the order of 2 mm for Low Risk Testing at 11 mrad

1:1 images of HB-LED sources
Low Risk BLH LED EHV Analysis

- Assume for LED chip evaluated at 200 mm:
  - LED Chip diameter $\approx 2.0$ mm
  - Assume gaussian ‘exitance’ profile
  - Field Stop at 200 mm $\approx 2.2$ mm

- Assess EHV due to power coupled through the field stop
  - 11 mrad field stop can substantially vignette certain source types

Field stop may ‘vignette’ source emission
## 11 mrad FOV – Gaussian Coupling

Simulation of Gaussian Profile Stop Coupling

<table>
<thead>
<tr>
<th>Required Field of View (mrad)</th>
<th>Test Distance (mm)</th>
<th>Assumed Field Stop Diameter (mm)</th>
<th>Nominal LED Chip Diameter (mm)</th>
<th>Gaussian Coupling Efficiency (%)</th>
<th>Gaussian Coupled Power (uW)</th>
<th>EHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>200</td>
<td>2.1</td>
<td>2</td>
<td>70.18</td>
<td>36.5</td>
<td>0.95</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>2.2</td>
<td>2</td>
<td>66.8</td>
<td>38.4</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>2.3</td>
<td>2</td>
<td>73.33</td>
<td>40.1</td>
<td>1.04</td>
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</tbody>
</table>

Assuming gaussian source exitance profile on field stop…

….Typically 5% EHV change per 100 µm field stop uncertainty
# 11 mrad FOV – Uniform Coupling

Simulation of Uniform Exitance Profile Field Stop Coupling

<table>
<thead>
<tr>
<th>Required Field of View (mrad)</th>
<th>Test Distance (mm)</th>
<th>Assumed Field Stop Diameter (mm)</th>
<th>Nominal LED Chip Diameter (mm)</th>
<th>Uniform Irradiance Coupled Power (uW)</th>
<th>Relative EHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>200</td>
<td>2.1</td>
<td>2</td>
<td>35</td>
<td>0.91</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>2.2</td>
<td>2</td>
<td>38.4</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>2.3</td>
<td>2</td>
<td>42</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Assuming uniform exitance profile on field stop…

….Typically 10% EHV change per 100 μm field stop uncertainty
Practical Data (FOV = 11 mrad)

<table>
<thead>
<tr>
<th>Field Stop Setting (mm)</th>
<th>Change in FOV Coupled Power - 11 mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.90</td>
<td>1.95</td>
</tr>
<tr>
<td>2.00</td>
<td>2.15</td>
</tr>
<tr>
<td>2.10</td>
<td>2.34</td>
</tr>
<tr>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td></td>
</tr>
</tbody>
</table>

Typically 5% EHV change per 100 μm field stop diameter increment.
EHV Variation for a Cool White LED

EHV variation for HB-LED Wavelength Offset

-6 -4 -2 0 2 4 6

EHV Value

Wavelength Shift (nm)
Spectral
EHV & Field Stop Coupling

- The smaller the required acceptance angle $\gamma$
  - The more stringent the precision on the field stop diameter setting (and location within field of view)
- Stop uncertainty implies uncertainty of power coupled through field stop
  - Implies increased uncertainty in radiance and EHV value
- 5% to 10% EHV uncertainty at $\gamma = 11$ mrad
  - For 100 $\mu$m change in field stop diameter
- Conservative approach
  - Use slightly larger field stop setting than specified
Summary of 62471
Uncertainties

- Optical radiation safety ‘EHV’ value
  Requires uncertainty value to be reported
  Adoption of conservative approach recommended
  i.e. ensure collection of (slightly) more radiant power

- Advance software simulation process
  Spectral ‘sliding’ & Stop size ‘dithering’
  Uncertainty of influencing parameters can be gauged and analyzed dynamically
## Typical 62471 EHV Uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influence on Blue Light Hazard Exposure Hazard Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre wavelength</td>
<td>$\approx 1%$ per every 10 nm offset</td>
</tr>
<tr>
<td>Spectral Linewidth</td>
<td>$\approx 2%$ per every 5 nm FWHM spread</td>
</tr>
<tr>
<td>Spectral radiant power</td>
<td>$\approx 2$ to $5%$ depending on detector type</td>
</tr>
<tr>
<td>Irradiance (Area of detector)</td>
<td>$\approx 2$ to $3%$ per 100$\mu$m @ 7 mm detector diameter</td>
</tr>
<tr>
<td>Radiance (area of field stop)</td>
<td>$\approx 5$ to $10%$ per 100$\mu$m @ 2.2 mm diameter (Low Risk Testing at 11 mrad FOV)</td>
</tr>
</tbody>
</table>
Thank you for your attention

With acknowledgement to EMRP
And thanks to LUX-TSI Ltd