Narrow-Band Spectra – High Efficacy

• Conventional all-phosphor spectra: **broad red emission** with long-red/near-IR tail
• Narrow (<35nm) red peak increases spectral efficiency by **10-20%**
• Red direct **emitters** and **narrow-band downconverters**: spectral efficiency w/ differing tradeoffs.

- Narrow-band red emission is valuable for high color quality at high efficacy, but may introduce system-level tradeoffs.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Red LEDs</th>
<th>Red NBDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Width</td>
<td>~15-20nm</td>
<td>~30-40nm</td>
</tr>
<tr>
<td>Thermal Droop (output 25→85°C)</td>
<td>25-35%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>System Color Mixing Impact</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Color Quality</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>
What About Narrow Green?

- **Efficacy benefit**: minimal compared to conventional green & red phosphors

  - Peaks are well within the eye response curve, thus **minimal** impact on efficacy (lm/W) with broad red peak.
  
  - Narrow green *and* narrow red bumps efficacy by 5-7%, but at what color quality cost?

  - Narrow green or cyan for emerging applications
    - **Cyan** NBDs (~480-500nm): melanopic impact
    - For >82% QY: higher EQE than direct cyan (~50%)
Spectral Engineering Beyond Efficacy

- Tailored narrow-band spectra may enable beneficial **physiological** or **psychological** responses.

- Example: spectra with “low” and “high” impact on melanopic eye response (cyan curve)

  - **Baseline**
    - 3000K
    - 80 CRI
    - 341 lm/W_{opt}
    - Melanopic
  
  - **“Enhanced Melanopic”**
    - 3000K
    - 80 CRI
    - 359 lm/W_{opt}
    - Melanopic

  - Higher spectral efficiency *and* higher melanopic impact (+15%)

- **Opportunity:** define metrics such as “melanopic/W” while evaluating impact on lm/W, lux/W, & color quality.

- New spectra will depend on the development of new **efficient** and **reliable** narrow-band (<40nm) emitters and downconverters from **cyan through red**.
Narrow-band Spectra – High-gamut Color Tuning

- Narrow emitters enable a wider **color tuning gamut**, with high spectral efficiency on or near the blackbody locus.

- **Challenges:**
  - **Color tuning:** requires investment in multi-driver control… this is now happening
  - **Fixture-to-fixture color consistency:** requires careful color point and intensity binning

**Conventional Phosphors**
- 3000K, 80 CRI
- 341 lm/W

**Narrow Emitters (30nm)**
- 3000K, 80 CRI
- 407 lm/W

Higher spectral efficiency and higher gamut
Color Quality – Beyond CRI

• So far spectra have been optimized for CRI $R_a$ and $R_g$.

• **IES TM-30**: quantifies color qualities beyond fidelity
  - Fidelity metric $R_f$ “penalizes” peaky/structured spectra
  - $R_f$ can’t be “gamed” as easily as CRI $R_a$
  - Gamut metric $R_g$ quantifies *averaged* enhanced gamut; $R_{cs,hj}$ sub-metrics tell *where* it’s happening

➢ *Color quality measures beyond CRI $R_a$ & $R_g$ should be assessed when specifying new spectra.*
Luminaire Optics: Present vs. Future

• SSL luminaire optics: designs evolving rapidly
  ▪ Improvements via “non-legacy” form factors
  ▪ Challenges still present in legacy form factors

• Optical Efficiency: 5-10% gains will be challenging

<table>
<thead>
<tr>
<th>Properties and efficiencies of white light production and direction by luminaire, then of use by end user</th>
<th>Present</th>
<th>Future (Targets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td>2015</td>
</tr>
<tr>
<td>Driver efficiency</td>
<td>%</td>
<td>0.88</td>
</tr>
<tr>
<td>Package efficacy (at 25°C)</td>
<td>lm/W</td>
<td>137</td>
</tr>
<tr>
<td>Thermal efficiency droop</td>
<td>%</td>
<td>0.88</td>
</tr>
<tr>
<td>Fixture (optical) efficiency</td>
<td>%</td>
<td>0.90</td>
</tr>
<tr>
<td>Luminaire Efficacy of White Light Production/Direction</td>
<td>lm/W</td>
<td>95</td>
</tr>
</tbody>
</table>

Note: these are ‘best case’, not average, efficiencies.

- Optical efficiency is just part of the equation!
  Illuminance & color uniformity, glare, utilization efficiency, & cost all matter.
System-level Color Mixing Tradeoffs

- Discrete narrow emitters require adequate color mixing prior to emission from the luminaire.

- Challenges:
  - Color over angle, particularly for directional emission
  - Color mixing at sufficient optical efficiency
  - Perceptible near-field (luminaire) color variation
  - Perceptible far-field (objects, surfaces) color variation

Achieving efficiency, uniformity, and directionality is a key challenge in SSL optical design.
Color Mixing: Old vs. New School

• Opportunity: color mixing of **discrete emitters** for enhanced **efficacy** and **color point tuning**

• “Old School”: **mixing chambers** with diffusers
  - Largely limited to ~Lambertian emission
  - Needs very low absorption mixing chamber
  - Adequate size/shape needed

• “New School”: **refractive** + **light-guiding** optics?
  - Could rely (at least in part) on **lossless TIR**
  - Could enable **low-profile** form factors and **cost reduction**
New Optics Designs - Lightguides

- **Lightguides**: should effectively couple LED emission, convey light with little/no loss, and efficiently extract (not just scatter!) light

- **LEDs**: compact size & high luminance
- **Lightguide**: low bulk absorption, smooth surfaces, mechanically stable
- **Extractors**: maximize first-pass extraction

LN4: “asymmetrical to diffuse” (using ceiling as optical element)
More Considerations: Utilization Efficiency, Glare

Utilization Efficiency:

- **Optical trade-offs** requiring innovation:
  - Low glare vs. high optical efficiency
  - Far-field illuminance vs. color uniformity
  - Aesthetic vs. functional/geometric limitations

Outdoor: some distributions well defined by guidelines.

Indoor: lux level guidelines used, but distributions “TBD”

Opportunities for application-optimized optics

```
TIR optic had parity lm/W but ~2x lx/W and reduced (by ~4x) high-angle glare
```

After W. Jiang and Kevin Schneider, LEDs Magazine 2/12.
Summary

- **Narrow-band emitters and downconverters**: promising efficacy and application-optimized spectral gains

- **Efficacy**
  - *Opportunity*: superior spectral efficiency
  - *Challenge*: significant improvements needed in materials efficiency and reliability from cyan to red

- **Color quality**
  - *Opportunity*: application-optimized color quality
  - *Challenge*: controls for optimized performance *and* application values

- **Optics design**
  - *Opportunity*: new aesthetics, better light utilization & new application values
  - *Challenge*: mitigate tradeoffs among efficiency; color mixing; uniformity; glare; …