Advances in Optics for Solid State Lighting

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Outline

- Optics and LEDs
- Design Methods
- Design examples
- Conclusions
Outline

• Optics and LEDs
• Design Methods
• Design examples
• Conclusions
### LEDs

**Features**
- White color >130 lm/W (and by mm²), ± 90° beam typically
- Lots of colors
- Low power consumption and long lifetime
- Instant switch on/off

**Specific challenges**
- Flux and luminance (depends on the application)
- Thermal
- Cost
- Non uniformities (multichip packages)
- Retrofitting?
Solid State Lighting

• Features
  • All applications (indoor/outdoor, accent, automotive, signaling…)
  • Imperfect results in the most demanding applications and retrofitting

<table>
<thead>
<tr>
<th>Year</th>
<th>SSL lighting</th>
<th>Traditional Lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>7%</td>
<td>93%</td>
</tr>
<tr>
<td>2020</td>
<td>25%</td>
<td>75%</td>
</tr>
</tbody>
</table>
Solid State Lighting

• Features
  • All applications (indoor/outdoor, accent, automotive, signaling…)
  • Imperfect results in the most demanding applications and retrofitting

• Specific challenges
  • Applications demanding high luminance
  • LED nature (emitting angles, thermal, costs)
  • Color mixing, illuminance uniformity and beam aesthetic goals

LED + luminaries

White point shift  Intensity Artifacts  Color Fringes  Multiple Shadows  Color Shadows
Optics

• Features
  • Primary optic + LED = light engine
  • Secondary optics = luminaire

• Manufacturing
  • Injection molding (PMMA and PC mostly)
  • Casting (silicone rubbers for domes)
• Optics and LEDs
• Design methods
• Design examples
• Conclusions
Non-imaging Optics (NIO)

• Features

  • Light power transfer between a source and a target
Non-imaging Optics (NIO)

- Features
  - Light power transfer between a source and a target

- Controlled beam angle
- Uniform illuminance
- Color mixing
Non-imaging Optics (NIO)

• Features
  • Light power transfer between a source and a target

![Diagram of non-imaging optics](image)
Non-imaging Optics

• Features

  • Light power transfer between a source and a target
  • Without the need of imaging, new possibilities arise: more efficient/compact/low cost optics…
Non-imaging Optics

• Features
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  • Without the need of imaging, new possibilities arise: more efficient/compact/low cost optics…
Non-imaging Optics

• Design

  • Fermat’s principle and derived/other physical laws: refraction, reflection and total internal reflection (TIR)
SMS method
SMS method
Köhler integration

• Two-stage design where input/output stage forms image of a preferred object point onto a point of the output/input stage
• Canonical example: two identical lenses imaging a point source at infinite (plane wavefronts) onto each other
Other design tools: Köhler integration

- When lenses are small and relatively far from the source, the illuminance is uniform over input lenses, so we have uniform intensity between $\pm \theta$ at the output.

* Square microlenses
• Optics and LEDs
• Design methods
• Design examples
• Conclusions
Köhler integration

• When lenses are small and relatively far from the source, the illuminance is relatively uniform over input lenses, so we have uniform intensity between $\pm \theta$ at the output.

• Köhler channels embedded into optics (patented)
The FK concentrator

Fresnel lens

Freeform secondary lens
FK irradiance uniformity

Simulated
Peak irradiance = 575 suns

Cell side
The Ventana™ Optical Train

- A complete off-the-shelf optics solution by Evonik and LPI
- Based on the best-in-class design: The FK concentrator

POE = primary optical element
SOE = secondary optical element
The Ventana™ reliability (可靠性)

POE:
- Evonik provides a 25 year warranty

SOE:
- The risk of UV solarization in Ventana™ is greatly reduced by splitting the incident beam into 4 channels.

Silicone:
- Ventana™ encapsulation can use catalyst-free silicones, which are the most stable ones.
LPI-Evonik Ventana™ Optical Train

Efficiency = **32.8%***
Fill Factor = 83.6%
Pm = 6.97 W
Isc = 2.80 A
Voc = 2.95 V
Irradiance = 847 W/m²
Entry Aperture = 256 m²

*No AR coatings; @Tcell=25°C
C3MJ Spectrolab cell bin 39%

C = 1,024x
α > ±1°
LPI V-GROOVE RXI (US patent 8,094,393)
V-GROOVE RXI

- Ultra-flat RXI collimator

Rays undergo…

- Refraction (R)
- Total Internal reflection (I)
- Reflection (X)
V-GROOVE RXI

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RXI

Photon funnel
V-GROOVE RXI

- Ultra-flat RXI collimator
V-GROOVE RXI

• Ultra-flat RXI collimator + advanced TIR utilization

Two TIR reflections
V-GROOVE RXI

• Ultra-flat RXI collimator + advanced TIR utilization

D. Grabovičkić, et al.
V-GROOVE RXI

- Metal-less Dielectric solid
- Very flat: depth/diameter = 0.25
- High efficiency: LOR = 90%
V-GROOVE RXI

• High collimation

• Fits with multi-chip packages: high flux, color mixing feasible thanks to “anomalous deflection”

RXI + LED RGGB: Far field pattern (ray trace)
V-GROOVE RXI

• High collimation

• Fits with multi-chip packages: high flux, color mixing feasible thanks to “anomalous deflection”

• Prototype photometry fits with simulations

Far field pattern picture  Far field measurement
LPI SHELL MIXER (PCT/US2811/052679)
KÖHLER CHANNELS

- Aligned arrays of lenses on the inner and outer surface of shell
- For every direction, the observer sees an apparent source with all chips welded

RGB chips

Köhler array

Far field image*
KÖHLER CHANNELS

• Aligned arrays of lenses on the inner and outer surface of shell
• For every direction, the observer sees an apparent source with all chips welded
KÖHLER CHANNELS

- Aligned arrays of lenses on the inner and outer surface of shell
- For every direction, the observer sees an apparent source with all chips welded
**LPI SHELL MIXER**

- Features
  - Hemispherical Köhler design for an universal Light engine
  - Light is integrated in optical channels
  - Preserves source apparent size and welds all chips within the integration zone (color mixing)
LPI SHELL MIXER

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+ luminaries

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Without shell  

With shell
LPI FREE-FORM RXI (US PATENT 7,460,895)
FREE-FORM RXI

• SMS 3D design
• Connects a extended source bundle with an asymmetric pattern
• Compact + high efficiency
FREE-FORM RXI

• SMS 3D design
• Connects a extended source bundle with an asymmetric pattern
• Compact + high efficiency

+ Köhler version
Advances in Optics for Solid State Lighting, OPTIC 2012, Dec. 6-8, 2012, Taipei
FREE-FORM RXI

• High-end applications

• Low beam: complex illumination problem owing to radical asymmetries, high flux on the road, sudden intensity drops (cut-off line)

• Standard pattern

$\text{I}_{\text{max}} = 31400 \text{ cd} \ 540 \text{ lm on road per headlight} $
FREE-FORM RXI

• High-end applications

• Low beam: complex illumination problem owing to radical asymmetries, high flux on the road, sudden intensity drops (cut-off line)

• RXI pattern

\[ I_{\text{max}} = 47000 \text{ cd} \] \[ 1290 \text{ lm on road per headlight} \]
A CPV example: The freeform XR concentrator

C = 1,000x
\[ \alpha = \pm 1.8^\circ \]

CAP~1

* The XR700 module developed by BOEING Co. and LPI (A. Plesniak et al. 34th IEEE PV Specialist Conference, 2010)
• SSL to dominate the market by 2020
• SSL and Nonimaging optics marry well
  • More performance
  • More tolerance
  • Simpler parts (mass production)
  • Lower Costs
Acknowledgments:

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Thank you