Shaping and Homogenization of LED White Light Using Aperiodic Scattering Cells Array

Huiying Zhong, Roberto Knoth, Christian Hellmann, Liangxin Yang, Frank Wyrowski
Background / Motivation

• Homogenization and shaping of LED white light is interesting for industrial applications.
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Task: Homogenization and shaping of LED white light!
Homogenization and shaping of LED white light is interesting for industrial applications.

Design methods:
   i. analytical design of periodic microlens arrays
      a. analytical model
      b. scalar diffraction theory
      c. parameters influence the intensity pattern

Background / Motivation

- Homogenization and shaping of LED white light is interesting for industrial applications.
- Design methods:
  i. analytical design of periodic microlens array
  ii. aperiodic arrangement of microlens array
     a. specific arrangement algorithm
     b. high homogeneity, low zeroth-order, low wavelength dependence

Background / Motivation

- Homogenization and shaping of LED white light is interesting for industrial applications.

Design methods:
- i. analytical design of periodic microlens array
- ii. aperiodic arrangement of microlens array

In this talk,
- i. advance modeling of the optical system
- ii. the design procedure starts from analytical design of a periodic microlens array
- iii. apply the probability function to achieve an aperiodic microlens array to increase the homogeneity
Optical Setup

LED + collimation optic

aperiodic refractive beam shaper array (aBSA)

camera detector

50 mm

angular spectrum (far field)
Optical Setup

LED + collimation optic

aperiodic refractive beam shaper array (aBSA)

camera detector

How to model the source, element and detector?

50mm

angular spectrum (far field)
Light Source: Lateral Modes

A set of point sources here
Light Source: Lateral Modes

shifted-elementary-mode concept

Light Source: Lateral Modes

\[ I(x, y, z) \propto \sum_{u, v, \ell} \left| D_\ell(\theta, \phi) \frac{\exp(ik_0 r_u)}{r_u} \right|^2 \]

\[ D_\ell(\theta, \phi) = -i\lambda_0/(2\pi)^2 \cdot \sqrt{I(\theta, \phi)} \]

Intensity distribution after collimation lens

Reference:
## Light Source: Lateral Modes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description / Value &amp; Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>name/type</td>
<td>Seoul Z-LED P4 from Seoul Semiconductors</td>
</tr>
<tr>
<td>partially coherent source type</td>
<td>Gaussian type planar source</td>
</tr>
<tr>
<td>collimation</td>
<td>TIR lens from Carclo Optics (part no. 10003)</td>
</tr>
<tr>
<td>spectrum</td>
<td>pure white light spectrum</td>
</tr>
<tr>
<td>FWHM radiant intensity</td>
<td>$9^\circ$</td>
</tr>
<tr>
<td>chip size</td>
<td>200 um x 200 um</td>
</tr>
</tbody>
</table>
post-processing step to calculate the weight on each sampled wavelength:

\[
\text{Spectrum's Integral} 
\approx \frac{1}{\lambda_N - \lambda_0} \sum_{i=0}^{N-1} (\lambda_{i+1} - \lambda_i) (I_{i+1} + I_i)
\]

\[
= \sum_{i=0}^{N}(\alpha_i \cdot I_i)
\]

with \( \alpha_i = \frac{\lambda_i - \lambda_{i-1}}{\lambda_i - \lambda_0} \)
## Components: Lens Array

Thin element (thin lens) approximation:
- paraxial light
- component element is thin enough

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description / Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell array aperture</td>
<td>20x20mm</td>
</tr>
<tr>
<td>pitch</td>
<td>to be designed</td>
</tr>
<tr>
<td>substrate thickness</td>
<td>1mm</td>
</tr>
<tr>
<td>substrate material</td>
<td>fused silica</td>
</tr>
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</table>
Components: Far Field Propagation

far field pattern is similar as angular spectrum of field before propagation.
Detector Modeling

• One LED contains several hundred modes. It takes hours per simulation. How to survive in parametric optimization?
  – Only a single, monochromatic elementary mode is propagation through the whole system. (speckle )
  – The other modes are included by using a convolution

\[
I_{\text{Detector}}(k_x, k_y) = \int_{-\infty}^{\infty} |A_t(k_x, k_y)|^2 w(k_x - k_{x0}, k_y - k_{y0}) dk_{x0} dk_{y0}
\]

\[
w(k_x, k_y) = \exp \left( -\frac{k_x^2}{\alpha^2} - \frac{k_y^2}{\beta^2} \right)
\]
Detector Modeling

• One LED contains several hundred modes. It takes hours per simulation. How to survive in parametric optimization?
  – Only a single, monochromatic elementary mode is propagation through the whole system. (speckle)
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Intensity: incoherent sum of all LED modes

intensity: convolution
Detector Modeling

- One LED contains several hundred modes. It takes hours per simulation. How to survive in parametric optimization?
  - Only a single, monochromatic elementary mode is propagation through the whole system. (speckle)
  - The other modes are included by using a convolution

Intensity: incoherent sum of all LED modes
NA of a single microlens array is given by the maximum divergent angle of desired target pattern

$$NA_t = \frac{\Delta k_t}{k}$$

Then the focal length of lenslet can be calculated

$$NA_t = \frac{p_{t,l}}{2f_{t,l}}$$
Design of Periodic Lens Array

• Lens array is periodic, so in far field, several diffraction orders of one single incident mode. Order separation is related to pitch size of lens array:

\[ \delta k_t = \frac{2\pi}{p_{t,l}}. \]

• Modes with different positions generate a shift in the angular spectrum. The maximum shift is given by LED chip size:

\[ \delta k_{t,\text{shift}} = \frac{h_t}{2f_c} k \]

• Criterial: \( \delta k_t \ll \delta k_{t,\text{shift}} \)
Result page of periodic lens array

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description / Value &amp; Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell array aperture</td>
<td>20x20mm</td>
</tr>
<tr>
<td>pitch</td>
<td>161.5 µm</td>
</tr>
<tr>
<td>FWHM window function δk_{t,shift}</td>
<td>1.56E6 1/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.1736</td>
<td>0.1785</td>
</tr>
<tr>
<td>focal length</td>
<td>465.02 µm</td>
<td>452.36 µm</td>
</tr>
<tr>
<td>profile height</td>
<td>15.62 µm</td>
<td>16.10 µm</td>
</tr>
<tr>
<td>simulated FWHM</td>
<td>4.60E6 1/m</td>
<td>4.84E6 1/m</td>
</tr>
<tr>
<td>conversion effc.</td>
<td>80.18</td>
<td>84.22</td>
</tr>
<tr>
<td>uniformity error</td>
<td>49.63</td>
<td>43.08</td>
</tr>
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</table>
Design of Aperiodic Lens arrays

- Center of each lenslet:

\[
x_i = i \times \Delta x + dx_i \\
y_j = j \times \Delta y + dy_j
\]

- The height of microlens array is determined by selecting the highest height value of current cell and the corresponding 8 adjacent cells:

\[
h(x, y) = \begin{cases} 
\max_{i-1 \leq i \leq i+1} \min_{j-1 \leq j \leq j+1} (h_{i,j}(x-x_i, y-y_j)) & \text{if } R < 0 \\
\min_{i-1 \leq i \leq i+1} \max_{j-1 \leq j \leq j+1} (h_{i,j}(x-x_i, y-y_j)) & \text{if } R > 0 
\end{cases}
\]
Design of Aperiodic Lens arrays

- During the optimization, we keep the parameters of each lenslet identical. The variables are:
  - Probability function

\[ P(X) = \sum_{l}^{L} w_l X^l \quad -0.5 \leq X \leq 0.5 \]
## Result Page of Aperiodic Lens Array

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<td>20x20mm</td>
</tr>
<tr>
<td>Pitch</td>
<td>161.5 µm</td>
</tr>
<tr>
<td>P(X): N</td>
<td>10</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Periodic</th>
<th>Aperiodic</th>
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<tbody>
<tr>
<td>Conversion effc.</td>
<td>84.22</td>
<td>84.97</td>
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<tr>
<td>Uniformity error</td>
<td>43.08</td>
<td>41.48</td>
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</table>
Extension:

- Arbitrary interface types can be used as single scattering cell.
Results:

<table>
<thead>
<tr>
<th>Component</th>
<th>Conversion eff.</th>
<th>Uniformity error</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLA</td>
<td>84.22</td>
<td>43.08</td>
</tr>
<tr>
<td>aMLA</td>
<td>84.97</td>
<td>41.48</td>
</tr>
<tr>
<td>SCA</td>
<td>92.07</td>
<td>19.60</td>
</tr>
<tr>
<td>aSCA</td>
<td>89.34</td>
<td>17.92</td>
</tr>
</tbody>
</table>
Conclusion

• Highlight of the design:
  – advanced source modeling
  – smart detector modeling

• Design procedure of MLA
  – analytical design of periodic lens array
  – parametric optimization of aperiodic lens array

• Outlook: Scattering cell with arbitrary shape
Acknowledgement

• Zentrales Innovationsprogramm Mittelstand (ZIM) - Kooperationsprojecte
Thanks for your attention!