Systematic design concept for AR&MR lightguide devices

*LightTrans International UG, **Wyrowski Photonics GmbH, ***University of Jena
Yesterday: Physical-optics analysis of lightguides for AR&MR glasses, F. Wyrowski, University Jena; C. Hellmann, Wyrowski Photonics UG (Germany); S. Steiner, R. Knoth, S. Zhang, LightTrans International UG (Germany)
Lightguide Modeling and Design

Selection of design criteria?
Lightguide Concept: In/Out Coupling

Gratings for in/out coupling.
Lightguide Concept: Exit Pupil Expansion
Lightguide Concept: Exit Pupil Expansion

Source

FOV

Eyebox

FOV

Source
Lightguide Concept: Fundamental Design Criteria

- Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.
Lightguide Concept: Fundamental Design Criteria

• Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.
• Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

Which one is more critical and should be prioritized?
Lightguide Concept: Fundamental Design Criteria

- FOV non-uniformity can be compensated by source (e.g. software)
- Eyebox non-uniformity is hard to compensate even by additional techniques (e.g. eye tracking)
Lightguide Concept: Fundamental Design Criteria

Source

W or Im

Angle (FOV)
Lightguide Concept: Fundamental Design Criteria

Source

Identical over eyebox

W or Im

Angle (FOV)

W or Im

Angle (FOV)
Lightguide Concept: Fundamental Design Criteria
Lightguide Concept: Fundamental Design Criteria

- Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.
Lightguide Concept: Modeling Task

Calculate radiance/illuminance per FOV mode including
- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence
Parametric Optimization of Lightguide Parameters

Parametric optimization
Lightguide Modeling and Design

- AR&VR in VirtualLab Fusion
- System configuration
- Lightguide modeling
- Lightguide design
- Optimization of incoupling grating

**Parametric optimization**
- **Parameter selection**
  - Optimization in batch mode in connection with any optimization tool
  - Distributed computing: Net server and cloud
- Initial design strategies
Cross Platform Simulation/Optimization - Python

**PYTHON**
- interactive access to batch mode files
- external mathematical functions and tools

**Batch mode files**
- execution of simulations
- optical parameters and simulation result storage

**VirtualLab Fusion**
- optical setup definition
- kernel simulation engine

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**Cross-platform simulation**

batch file
xml files
...

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**Python**

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**VirtualLab Fusion**
Cross Platform Simulation/Optimization - MATLAB

MATLAB
- interactive access to batch mode files
- external mathematical functions and tools

Batch mode files
- execution of simulations
- optical parameters and simulation result storage

VirtualLab Fusion
- optical setup definition
- kernel simulation engine

MATLAB

VirtualLab Fusion

cross-platform simulation

batch file
xml files
...
Cross Platform Simulation/Optimization - optiSLang

optiSLang
- interactive access to batch mode files
- internal mathematical functions and tools

Batch mode files
- execution of simulations
- optical parameters and simulation result storage

VirtualLab Fusion
- optical setup definition
- kernel simulation engine

cross-platform simulation
**Cloud Computing**

VirtualLab supports cloud computing on Azure cloud:
- Cluster with e.g. 8 or more nodes
- Windows Machines with e.g. Windows Server 2012 R2 OS
- Software: HPC Pack 2012 (Microsoft tool) (High Performance Computing)

The usage of cloud computing enables a speed up of the simulation, which can be scaled by the size of the cluster in use.
Parametric Optimization by VirtualLab & External Tools

Provides full flexibility by a powerful combination of tools to find the best solution for your lightguide architecture
Parametric Optimization of Lightguide Parameters

Parametric optimization
Initial design, e.g.
• Inverse approaches
• Functional design

Parametric optimization

In suitable combination
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

- System configuration
  - Lightguide modeling
    - Lightguide design
      - Parametric optimization
        - Initial design strategies
          - Grating region layout: k-domain circle
          - Beam density evaluation: eye box uniformity
            - Grating (EPE, outcoupling) optimization: Part I
            - Grating (EPE, outcoupling) optimization: Part II
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Lightguide modeling

Lightguide design

Parametric optimization

Initial design strategies

Grating region layout: k-domain circle

Beam density evaluation: eye box uniformity

Grating (EPE, outcoupling) optimization: Part I

Grating (EPE, outcoupling) optimization: Part II

\[ G = \left( \frac{2\pi}{p_x}, \frac{2\pi}{p_y} \right)^T \]
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Lightguide modeling

Lightguide design

1: k-Layout Visualization

Physical Settings | View Settings

Environment
- Wavelength: 552 nm
- Surrounding Medium: Air in Homogeneous Medium
- Light Guide Medium: S-LAH179_Dhara_2016 in Homogeneous Medium

Field of View
- Width x Height: 32 x 10°
- Offset: 0°

Grating Parameters
- Incoupling Grating: 300 nm, 0°, 1°
- Eye Pupil Expander: 200.7 nm, -45°, -1°
- Outcoupling Grating: 300 nm, -90°, 1°

Optimization

K-space strategies

Region layout: k-domain circle

Intensity evaluation: eye box uniformity

Related work: EPE, outcoupling

Combination: Part I

Combination: Part II
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion → System configuration → Lightguide modeling → Lightguide design

- Parametric optimization
- Initial design strategies
  - Grating region layout: k-domain circle
  - Beam density evaluation: eye box uniformity
    - Grating (EPE, outcoupling) optimization: Part I
    - Grating (EPE, outcoupling) optimization: Part II
Eyebox Uniformity vs. Beam Density

outcoupled light

behind eye pupil
• Per eye position \((x, y)\) in eyebox the flux into the eye per FOV angle \((\theta_x, \theta_y)\) is calculated, which represents the radiance \(L_e\).

• The uniformity error \(\Omega(\theta_x, \theta_y)\) is defined as the contrast of \(L_e\):

\[
\Omega(\theta_x, \theta_y) = \frac{\text{max}_{x,y} L_e(\theta_x, \theta_y; x, y) - \text{min}_{x,y} L_e(\theta_x, \theta_y; x, y)}{\text{max}_{x,y} L_e(\theta_x, \theta_y; x, y) + \text{min}_{x,y} L_e(\theta_x, \theta_y; x, y)}
\]
Eyebox Uniformity vs. Beam Density

Initial investigation:

- Assume ideal gratings which provide perfectly uniform beams.
- Concentrate on beam density vs.
  - Thickness of lightguide
  - Beam size (light engine)
  - Off-axis angle incoupling
Irradiance in eyebox: FOV (0°, 0°)
Eyebox Uniformity vs. Beam Density

Irradiance in eyebox: FOV (0°, 0°)
Eyebox Uniformity vs. Beam Density

Irradiance in eyebox: FOV (0°, 0°)

Radiance FOV (0°, 0°)
Uniformity: 10.5%
Eyebox Uniformity vs. Beam Density: Single Wavelength

Source
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21
Eyebox Uniformity vs. Beam Density: Single Wavelength

**Source**
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

**Detector**
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Beams per FOV/wavelength are correlated!
Eyebox Uniformity vs. Beam Density: Bandwidth 1nm

**Source**
- Plane Wave ($0^\circ$, $0^\circ$)
- **Bandwidth – 1nm**

**Detector:**
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - $21 \times 21$

![Graph showing Eyebox Uniformity vs. Beam Density with Bandwidth 1nm](image)
Eyebox Uniformity vs. Beam Density: Bandwidth 10nm

Source:
- Plane Wave (0°, 0°)
- Bandwidth – 10nm

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21
Eyebox Uniformity vs. Beam Density: Bandwidth 10nm

**Source**
- Plane Wave (0°, 0°)
- Bandwidth – 10nm

**Detector**
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Field tracing provides highly resolved light distributions fast.
Uniformity vs. Beam Density – Comparison Bandwidths

![Graph showing Uniformity Error (%) vs. Beam Density for different bandwidths: Single Wavelength, 1nm Bandwidth, 10nm Bandwidth. The graph illustrates how bandwidth affects uniformity error.]
Eyebox Uniformity vs. Beam Density: FOV 1

Source:
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21
Eyebox Uniformity vs. Beam Density: FOV 2

**Source**
- Plane Wave (6°, 3°)
- Single Wavelength (532nm)

**Detector:**
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

**Uniformity Error (%)**

**Beam Density**
Eyebox Uniformity vs. Beam Density: FOV 3

Source:
- Plane Wave \((-6^\circ, -3^\circ)\)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Uniformity Error (%)

Beam Density
Uniformity vs. Beam Density: Comparison Different FOVs
Specified:
- Beam size
- Lightguide thickness
- Off-axis angle
Strategy:
- Optimize grating parameters per FOV angle
- Combine results
Grating Design for FOV Angle (0°, 0°)

Beam footprints
Grating Design per FOV Angle: Flux Control

Per footprint of beam:
- Control percental flux into required directions
- Optimize local grating parameters to obtain required flux
Grating Design per FOV Angle: Grating Analysis and Selection

Calculation of Rayleigh matrix for given input beam parameters

\[
\begin{pmatrix}
E_{x,\text{out}} \\
E_{y,\text{out}}
\end{pmatrix}_{k_{\text{out},m}} =
\begin{bmatrix}
R_{xx} & R_{yx} \\
R_{xy} & R_{yy}
\end{bmatrix}
\cdot
\begin{pmatrix}
E_{x,\text{arb,in}} \\
E_{y,\text{arb,in}}
\end{pmatrix}_{k_{\text{in}}}
\]
Grating Design per FOV Angle: Grating Analysis and Selection

Scan of grating parameters: e.g. fill factor (x) and height (y)

Calculation of Rayleigh matrix for given input beam parameters

\[
\begin{pmatrix}
E_{x,\text{out}} \\
E_{y,\text{out}}
\end{pmatrix}_{k_{\text{out},m}} =
\begin{bmatrix}
R_{xx} & R_{yx} \\
R_{xy} & R_{yy}
\end{bmatrix}
\cdot
\begin{pmatrix}
E_{x,\text{arb,in}} \\
E_{y,\text{arb,in}}
\end{pmatrix}_{k_{\text{in}}}
\]
• Selection of grating parameters per footprint to obtain required fluxes.
Grating Design per FOV Angle: Grating Analysis and Selection

- Storage of Rayleigh matrices in lookup table.
- Can be applied to arbitrary polarization for optimizing grating parameters.

\[
\begin{pmatrix}
E_{x,\text{out}} \\
E_{y,\text{out}}
\end{pmatrix}_{k_{\text{out},m}} = \begin{bmatrix}
R_{xx} & R_{yx} \\
R_{xy} & R_{yy}
\end{bmatrix} \cdot \begin{pmatrix}
E_{x,\text{arb, in}} \\
E_{y,\text{arb, in}}
\end{pmatrix}_{k_{\text{in}}}
\]
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Linearly polarized in x-direction
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Incident light at grating interaction (uniform polarization)
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Partial TIR and partial zeroth order of grating!

Incident light at grating interaction (uniform polarization)
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Incident light at grating interaction (non-uniform polarization)
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Incident light at grating interaction (non-uniform polarization)
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

Incident light at grating interaction (non-uniform polarization)
Lightguide Modeling and Design: Grating Optimization

Strategy:
• Optimize grating parameters per FOV angle
Grating Design for FOV Angle ($0^\circ, 0^\circ$)

<table>
<thead>
<tr>
<th>Merit Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV Angle</td>
<td>$\alpha = 0^\circ; \beta = 0^\circ$</td>
</tr>
<tr>
<td>Uniformity Error</td>
<td>0.34%</td>
</tr>
</tbody>
</table>
Optimized Grating Parameter EPE Grating

Optimized Fill Factors

Optimized Modulation Depth
Optimized Grating Parameter Outcoupling Grating

- Optimized Fill Factors

- Optimized Modulation Depth
Grating Design for FOV Angle (5°, 3°)

<table>
<thead>
<tr>
<th>Merit Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV Angle</td>
<td>$\alpha = 5^\circ; \beta = 3^\circ$</td>
</tr>
<tr>
<td>Uniformity Error</td>
<td>0.61%</td>
</tr>
</tbody>
</table>
Optimized Grating Parameter EPE Grating

Optimized Fill Factors

Optimized Modulation Depth
Optimized Grating Parameter Outcoupling Grating

Optimized Fill Factors

Optimized Modulation Depth
EPE Grating Design for Different FOV: Height
Strategy:
• Optimize grating parameters per FOV angle
Strategy:

- Optimize grating parameters per FOV angle
- Combine results
Combination of Different FOV Designs

Voronoi Segmentation

Source: www.wikipedia.com
Optimized Grating Parameter EPE Grating

Optimized Fill Factors

90% 600nm

10% 100nm

Optimized Modulation Depth
Optimized Grating Parameter Outcoupling Grating

Optimized Fill Factors

Optimized Modulation Depth
Result Combination of Modes (Segmentation)

Each color indicates segments, which were optimized for one mode.
Result Combination of Modes (Segmentation)
Result Combination of Modes (Segmentation)
Result Combination of Modes (Segmentation)
Result Combination of Modes (Segmentation)
Result Combination of Modes (Segmentation)
Result Combination of Modes (Segmentation)
Final Design Results Mode #1 + #2

<table>
<thead>
<tr>
<th>Mode</th>
<th>Merit Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>FOV Angle</td>
<td>$\alpha = 0^\circ; \beta = 0^\circ$</td>
</tr>
<tr>
<td></td>
<td>Uniformity Error</td>
<td>43.90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Merit Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>FOV Angle</td>
<td>$\alpha = 5^\circ; \beta = 3^\circ$</td>
</tr>
<tr>
<td></td>
<td>Uniformity Error</td>
<td>45.61%</td>
</tr>
</tbody>
</table>
Result Combination of Modes (Segmentation)
Parametric Optimization and Initial Design

Initial design, e.g.
• Inverse approaches
• Functional design

Parametric optimization

In suitable combination
Steady R&D to tackle the uniformity challenge.
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion → System configuration → Lightguide modeling → Lightguide design

- Parametric optimization
- Initial design strategies
  - Grating region layout: k-domain circle
  - Beam density evaluation: eye box uniformity
  - Grating (EPE, outcoupling) optimization: Part I
  - Direct design for selected FOV modes
  - Combination of results
  - Grating (EPE, outcoupling) optimization: Part II

Steady R&D to tackle the uniformity challenge.

Why this task is so complex?
Telescope System

**FOV modes behave somehow well-sorted**

### System parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification</td>
<td>5.5X</td>
</tr>
<tr>
<td>Field of view</td>
<td>4°</td>
</tr>
</tbody>
</table>

\[
F / \# = \frac{f'}{D'}
\]

where, D' is the diameter of the entrance pupil

### Objective group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>100 mm</td>
</tr>
<tr>
<td>F/#</td>
<td>2.8</td>
</tr>
<tr>
<td>number of lenses</td>
<td>4</td>
</tr>
</tbody>
</table>

### Eyepiece group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>18.3 mm</td>
</tr>
<tr>
<td>Exit Pupil Diameter</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>number of lenses</td>
<td>5</td>
</tr>
</tbody>
</table>

Lens source: A_019 and C_001 in Zebase
Design for Multiple FOV Modes: Waveguide
Design for Multiple FOV Modes: Waveguide

FOV modes laterally “randomly” mixed up
Initial design, e.g.
- Inverse approaches
- Functional design

Parametric optimization

In suitable combination
Thank You!