Innovative systematic design approach for lightguide devices for AR & MR-applications (11310-16)

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Teams

LightTrans (since 1999)
- Optical technologies development
- Technical support, seminars, and trainings
- Engineering projects
- Distribution of VirtualLab Fusion, together with distributors worldwide

LightTrans International (since 2014)

photo from wikitravel

Jena
Optical Design Software and Services

Booth #4545
(German pavilion)
Physical-Optics System Modeling

Solve Maxwell’s equations for given source field and components.
Solution of Maxwell’s equations with one field solver, e.g. FEM, FMM, or FDTD, for entire system not feasible because of numerical effort!
How to obtain a reliable and fast physical optics solution - whenever possible?
Connecting Optical Technologies / Maxwell Solvers

- Field Solver Lenses, …
- Field Solver Prisms, …
- Field Solver gratings, …
- Field Solver micro- and nano-structures
- Field Solver fibers, …

Homogeneous medium, like air or vacuum
Connecting Optical Technologies / Maxwell Solvers

Problem:
Application of a single field solver, e.g. FEM or FDTD, to the entire system: Unrealistic numerical effort

Solution:
• Decomposition of system and application of regional field solvers.
• Interconnection of different solvers and so to solve the complete system.
Problem:
Application of a single field solver, e.g. FEM or FDTD, to the entire system:
Unrealistic numerical effort

Solution:
• Decomposition of system and application of regional field solvers.
• Interconnection of different solvers and so to solve the complete system.

Fast Physical Optics Software by Connecting Field Solvers
Lightguide Modeling and Design

Today 4:10 pm: **Physical-optics analysis of lightguides for augmented and mixed reality glasses**
Lightguide Modeling and Design

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

- Parametric optimization
- Initial design strategies
Lightguide Modeling and Design

Design demands & constraints: e.g.
- Constraints of lateral layout & dimensions
- Desired optical parameters (e.g. FoV, wavelength)
- Desired optical performance (efficiency & uniformity)
- Type of gratings and range of parameters
Lightguide Modeling and Design

Design demands & constraints: e.g.
- Constraints of lateral layout & dimensions
- Desired optical parameters (e.g. FoV, wavelength)
- Desired optical performance (efficiency & uniformity)
- Type of gratings and range of parameters

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

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

- Uniformity of radiance/illuminance 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 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

Identical over eyebox

Source

W or Im

Angle (FOV)

W or Im

Angle (FOV)
Lightguide Concept: Fundamental Design Criteria

- Source

- W or lm vs. Angle (FOV)
  - Identical over eyebox

- W or lm vs. Angle (FOV)
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


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 and Initial Design

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

In suitable combination

Parametric optimization
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
     - Environment
       - Wavelength: 592 nm
     - Surrounding Medium
       - Air in Homogeneous Medium
     - Light Guide Medium
       - S-LAH79_Ohara_2016 in Homogeneous Medium
   - Field of View
     - Width x Height: 32 × 10°
     - Offset: 0°
   - Grating Parameters
     - Period: 300 nm
     - Rotation Angle: 0°
     - Grating Order: 1

Optimization

- Strategies
  - Region layout: k-domain circle
- Intensity evaluation: eye box uniformity

EPE, outcoupling

- Solution: Part I
- Solution: 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
Eyebox Uniformity vs. Beam Density

- 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 \(L_e\):

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

Irradiance in eyebox: FOV (0°, 0°)
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°, 0°)
- Bandwidth – 1nm

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

Uniformity Error (%) vs. Beam Density
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
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
Eyebox Uniformity vs. Beam Density: FOV 3

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

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

\[
\begin{pmatrix}
E_{x,\text{out}} \\
E_{y,\text{out}} \\
\end{pmatrix}_k =
\begin{bmatrix}
R_{xx} & R_{yx} \\
R_{xy} & R_{yy} \\
\end{bmatrix}
\begin{pmatrix}
E_{x,\text{arb,\text{in}}} \\
E_{y,\text{arb,\text{in}}} \\
\end{pmatrix}_k
\]
• 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)
Strategy:
- Optimize grating parameters per FOV angle
Grating Design for FOV Angle (0°, 0°)

<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

- 90% (600nm)
- 10% (100nm)

Optimized Modulation Depth
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 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

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>
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</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.
Conclusion

- Physical-optics modeling of lightguides enables the consideration of all effects that have to be taken into account during the design development.
- Parametric optimization can be done but is often slow due to lack of good initial solution and numerous parameters of the system.
- VirtualLab allows for new systematic design concepts for lightguide devices, which provide a strategy to obtain appropriate initial system configurations.
- The combination of physical-optical modeling, systematic design and parametric optimization will provide the optimal system design.
Thank You!
Steady R&D to tackle the uniformity challenge.

Why this task is so complex?
Telescope System

FOV modes behave somehow well-sorted

<table>
<thead>
<tr>
<th>System parameters</th>
<th></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>

<table>
<thead>
<tr>
<th>Objective group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length $f_{objective}$</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>

<table>
<thead>
<tr>
<th>Eyepiece group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length $f_{eyepiece}$</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

$F / \# = \frac{f'}{D'}$

where, D 'is the diameter of the entrance pupil
Design for Multiple FOV Modes: Waveguide
Design for Multiple FOV Modes: Waveguide

FOV modes laterally “randomly” mixed up
Parametric Optimization and Initial Design

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

Parametric optimization

In suitable combination