Physical-optics analysis of lightguides for augmented and mixed reality glasses (11310-38)

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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)
Optical Design Software and Services

Booth #4545
(German pavilion)
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!
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
Problems:
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.
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.

Fast Physical Optics Software by Connecting Field Solvers

LightTrans International
Example of Plate/Etalon

Different lightpaths because of non-sequential model

Sum of mutually coherent fields per lightpath

Fig. 9.41 Phase shifts arising purely from the reflections (internal $\theta_i < \theta_0$).

At point $P$, is then

$E_{0f} = E_{0f} - (E_{0fr}r' + E_{0fr}r' + E_{0fr}r' + \cdots)$

Or

$E_{0f} = E_{0f} - E_{0fr}r'(1 + r^2 + r^4 + \cdots)$.
Fig. 9.41  Phase shifts arising purely from the reflections (internal \( \theta_i < \theta_c \)).

at point \( P \), is then

\[ E_{0r} = E_d + (E_d r tr' + E_d r^2 t' + E_d r^3 t' + \cdots) \]

or

\[ E_{0r} = E_d - E_d r tr' (1 + r^2 + r^4 + \cdots). \]

Fig. 9.45  Any function.
Connecting Field Solvers: Tilted Planar-Planar Surfaces

- Etalon configuration: planar-planar (tilted)
  - Center thickness: 100 µm
  - Tilt of first surface: 0.1°
Connecting Field Solvers: Tilted Planar-Planar Surfaces

etalon configuration
planar-planar (tilted)
- center thickness 100 µm
- tilt of first surface 0.1°

Field Solvers
1. diffractive, Fresnel, meta lenses
2. HOE, CGH, DOE
3. SLM & adaptive components
4. micro lens & freeform arrays
5. diffusers
6. scatterer
7. waveguides & fibers
8. curved interface
9. planar interface
10. crystals & anisotropic components
11. nonlinear components
12. free space
Connecting Field Solvers: Tilted Planar-Planar Surfaces

etalon configuration
planar-planar (tilted)
- center thickness 100 µm
- tilt of first surface 0.1°

parallel surfaces
Connecting Field Solvers: Tilted Planar-Planar Surfaces

etalon configuration
planar-planar (tilted)
- center thickness 100 µm
- tilt of first surface 0.1°

Linear interference fringes appear due to linear change of etalon thickness.

parallel surfaces
first surface tilt by 0.1°
Connecting Field Solvers

etalon configuration
cylindrical-planar
- center thickness 100 µm
- cylindrical (x) surface radius 1 m

Field Solvers

1. crystals & anisotropic components
2. nonlinear components
3. free space
4. plane interface
5. curved interface
6. apertures & boundaries
7. gratings
8. diffractive, Fresnel, meta lenses
9. HOE, CGH, DOE
10. SLM & adaptive components
11. micro lens & freeform arrays
12. waveguides & fibers
13. scatterer
14. diffractive beam splitters

x
z
30°
Connecting Field Solvers: Cylindrical-Planar Surfaces

etalon configuration cylindrical-planar
- center thickness 100µm
- cylindrical (x) surface radius 1m

Polarization-dependent effect on the interference is considered in the simulation.
Connecting Field Solvers: Spherical-Planar Surfaces

etalon configuration spherical-planar
- center thickness 100\,\mu m
- spherical (x\&y) surface radius 1\,m

Non-sequential field tracing simulation of etalons allows the consideration of arbitrary surface types.
Connecting Field Solvers: Spherical-Planar Surfaces

etalon configuration spherical-planar
- center thickness 100 µm
- spherical (x&y) surface radius 1 m

Non-sequential field tracing simulation of etalons allows the consideration of arbitrary surface types.

Field Tracing: Connecting Field Solvers
Lightguide Concept

Source

FOV

Eyebox

FOV
Lightguide Concept: Fundamental Detectors

- Radiance/illuminance (per pupil area) in eyebox
- PSF/MTF over eye position in eyebox
- Photometry, radiometry, image resolution, color, … *field tracing provides high flexibility to apply customized detector functions*
Lightguide Concept: Modeling Task

Evaluate e.g. radiance, illuminance, PSF/MTF including
- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence
Typical Modeling Situation for AR&MR Lightguide

- Free space prisms, plates, cubes, ...
- Lenses & freeforms
- Apertures & boundaries
- Gratings
- Diffractive, Fresnel, meta lenses
- HOE, CGH, DOE
- Micro lens & freeform arrays
- SLM & adaptive components
- Diffractive beam splitters
- Scatterer
- Waveguides & fibers
- Nonlinear components
- Crystals & anisotropic components
- Free space
- Prisms, plates, cubes, ...
- Lenses & freeforms
- Apertures & boundaries
- Field Solvers
Interference and coherence effects
Correlation between Modes in Modeling

- FOV mode (one image pixel) represents electromagnetic field which consists of
  - Fully coherent modes per wavelength: spectral modes
  - Stationary sources: Spectral modes are mutually uncorrelated
  - Degree of polarization: Representation by two uncorrelated modes per spectral mode
- Each spectral mode propagates through lightguide and is split numerous times:
  - Channel modes (beams in eyebox)
  - Channel modes per spectral mode are mutually correlated!
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Light engine

(Stack of) Lightguide(s)

Surface modulation function (SMF)

Detectors

Lightguide modeling

Optimization of incoupling grating

Lightguide design
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Lightguide modeling

Lightguide design

Optimization of incoupling grating

- Light engine
  - Any source model can be applied in lightguide modeling
    - Any degree of coherence
    - Any degree of polarization
  - Configuration and modeling of light engine

(Stack of) Lightguide(s)

- Surface modulation function (SMF)
- Detectors

A general approach to the analysis and description of partially polarized light in rigorous grating theory

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Shifted-elementary-mode representation for partially coherent vectorial fields

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Correlation between Modes in Modeling

- Correlation
  - FOV mode
    - Spectral mode 1
      - Channel mode 1
        - Channel mode m
          - Channel mode M
    - ......
    - Spectral mode j
      - Channel mode 1
        - Channel mode m
          - Channel mode M
    - ......
Levola Type Geometry of Eye Pupil Expansion (EPE)
Levola Type Geometry of Eye Pupil Expansion (EPE)

Multiple Mini-Mach-Zehnder Systems
Mini Mach-Zehnder Interferometer Lightpaths: Channel Modes
Lightguide Setup & Evaluation of Outcoupled Light

Exemplary Outcoupled Light
Outcoupled Light Modes Passing Through Eye Pupil

- Marginal area of outcouling grating region due to beams hitting the edge of any grating region. The further propagation varies for the different light portions; this causes these segmented beam footprints.

- Light passing the eye pupil, each of these beam footprints derives from multiple light modes from different light paths.
Outcoupled Light Modes Passing Through Eye Pupil

Boundary effects should be included in high resolution

light passing the eye pupil
Outcoupled Light Modes Passing Through Eye Pupil

Boundary effects should be included in high resolution

light passing the eye pupil
Outcoupled Light Modes Passing Through Eye Pupil

Boundary effects should be included in high resolution
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.
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For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.

Assumption of uncorrelated modes leads to wrong result!
For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.
Light Modes Passing Through Eye Pupil: 1nm Bandwidth

Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.
Light Modes Passing Through Eye Pupil

...of a laser diode (~1nm)

...of a VCSEL (~20nm)

...of an LED (~40nm)

Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.
Light Modes Passing Through Eye Pupil

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...of a VCSEL (~20nm)
...of an LED (~40nm)

Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.
Polarization effects
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!
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)
PSF and MTF evaluation
Light Modes Passing Through Eye Pupil

...of a laser diode (~1nm)

...of a VCSEL (~20nm)

...of an LED (~40nm)

Pupil is partly filled with mutually correlated channel modes per uncorrelated spectral modes.
Results: Full Pupil Illumination

Ideal Eye Model
- pupil diameter = 4 mm
- ideal lens with focal length = 17 mm
Results: Full Pupil Illumination

Ideal Eye Model
- pupil diameter = 4 mm
- ideal lens with focal length = 17 mm
Results: FoV = (0°; 0°), Monochromatic 532nm

- Outcoupled light behind eye pupil
- PSF @ retina
- 2D MTF
- 1D MTF along 0° (X)
- 1D MTF along -45°
Results: FoV = (0°; 0°), Spectrum 1 nm Bandwidth (24 samples)
Results: FoV = (0°; 0°), Spectrum 10 nm Bandwidth (100 samples)

- Outcoupled light behind eye pupil
- PSF @ retina
- 2D MTF
- 1D MTF along 0° (X)
- 1D MTF along -45°
Light Modes Passing Through Eye Pupil

...of a laser diode (~1 nm)

...of a VCSEL (~20 nm)

...of an LED (~40 nm)

For one wavelength and one FOV the pupil is partly filled with mutually correlated channel modes.
Diffractive in Lightguide
Typical Modeling Situation for AR&MR Lightguide

- Free space prisms, plates, cubes, ...
- Lenses & freeforms, apertures & boundaries
- Gratings
- Diffractive, Fresnel, meta lenses
- HOE, CGH, DOE
- Micro lens & freeform arrays
- SLM & adaptive components
- Diffusers
- Scatterer
- Diffractive beam splitters
- Waveguides & fibers
- Nonlinear components
- Crystals & anisotropic components
- Free space

Field Solvers

Imager → 1 → 2 → 3 → 4 → 5 → Eye
Typical Modeling Situation for AR&MR Lightguide

- Free space prisms, plates, cubes, ...
- Lenses & freeforms
- Gratings
- Diffractive, Fresnel, meta lenses
- HOE, CGH, DOE
- Micro lens & freeform arrays
- SLM & adaptive components
- Diffractive beam splitters
- Scattered
- Waveguides & fibers
- Apertures & boundaries
Typical Modeling Situation for AR&MR Lightguide
Cascaded Diffraction in Lightguide Modeling: Layout

Ray tracing illustration

Grating regions: variation of diffraction efficiency per segment
Cascaded Diffraction in Lightguide Modeling: Layout

Lightguide: Front View

Lightguide: Top View

Ray tracing illustration

Grating regions: variation of diffraction efficiency per segment
Lightguide Modeling: Suppressed Diffraction Effects (Homeomorphic)

Lightguide: Front View

Intensity (homeomorphic model)

\[ I(\rho) = |E_x(\rho)|^2 + |E_y(\rho)|^2 + |E_z(\rho)|^2 \]
Lightguide Modeling: Suppressed Diffraction Effects (Homeomorphic)

Lightguide: Front View

Intensity (homeomorphic model)

\[ I(\rho) = |E_x(\rho)|^2 + |E_y(\rho)|^2 + |E_z(\rho)|^2 \]
Lightguide Modeling: Diffraction Effects Included

Lightguide: Front View

Intensity (homeomorphic model)

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Lightguide Modeling: Diffraction Effects Included

$$I(\rho) = |E_{x}(\rho)|^2 + |E_{y}(\rho)|^2 + |E_{z}(\rho)|^2$$
Conclusion

• Connecting field solvers enables practical and fast physical-optics modeling of lightguides for AR&VR.
• VirtualLab Fusion provides all demanded modeling techniques on one single platform
  − Ray tracing
  − Physical-optics modeling
• Dependent on the lightguide architecture and the light engine, interference, coherence, polarization, and diffraction effects can be important and are fully included in modeling.

Steady R&D in lightguide modeling and design.
Thank You!
Energy conservation per spectral mode

Ultimate test: Evaluation of overall flux through all surfaces of waveguide must provide efficiency close to 100%
Modeling Task: In- and Outcoupling

Grating regions: Rigorous modeling by FMM!

Slanted grating profile
Result by 3D Ray Tracing (Working Orders)

Ray tracing illustration of desired lightpath.
Result by 3D Ray Tracing (All Orders)

Ray tracing illustration including all lightpaths caused by higher grating orders.
Rigorous Overall Efficiency Evaluation

• Physical-optics analysis of all lightpaths.
• Combination including polarization and coherence!

<table>
<thead>
<tr>
<th>Detector</th>
<th>Calculated Efficiency</th>
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<tbody>
<tr>
<td>Transmission @ Incoupling</td>
<td>0.416%</td>
</tr>
<tr>
<td>Reflection @ Incoupling</td>
<td>11.997%</td>
</tr>
<tr>
<td>Side Wall #1</td>
<td>1.194%</td>
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<tr>
<td>Side Wall #2</td>
<td>6.778%</td>
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<tr>
<td>Reflection @ Outcoupling</td>
<td>77.983%</td>
</tr>
<tr>
<td>Transmission @ Outcoupling</td>
<td>1.546%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99.915%</strong></td>
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