Optical design of beam delivery systems for cw and pulsed lasers

R. Knoth\textsuperscript{2}, C. Hellmann\textsuperscript{1}, S. Zhang\textsuperscript{2}, D. Kühn\textsuperscript{3}, F. Wyrowski\textsuperscript{3}

\textsuperscript{1}Wyrowski Photonics UG
\textsuperscript{2}LightTrans International UG
\textsuperscript{3}University of Jena, Applied Computational Optics
Who, Where, What?

Applied Computational Optics Group R&D in optical modeling and design with emphasis on physical optics
Who, Where, What?

Wyrowski Photonics
Development of fast physical optics software
VirtualLab Fusion
Who, Where, What?

LightTrans
- Distribution of VirtualLab Fusion, together with distributors worldwide
- Technical support, seminars, and trainings
- Engineering projects
All techniques shown in this talk are available in VirtualLab Fusion Software or/and as Consulting & Engineering Services!

Hall 4, Booth 4B71.1
Table of Content

1. Geometric and diffractive branch of physical optics
2. Modeling and design of beam delivery systems by physical optics
3. Examples
Geometric and diffractive branch of physical optics

The geometric Fourier transform
Physical and Geometrical Optics: Traditional Understanding
Physical and Geometrical Optics: Traditional Understanding

- **Physical optics:**
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations.

- **Geometrical/ray optics:**
  - Light is represented by mathematical rays (with energy flux) which
  - are governed by Fremat’s principle which is mathematically expressed by ray equation.
Physical and Geometrical Optics: Traditional Understanding

• Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations.

• Geometrical/ray optics:
  - Light is represented by mathematical rays (with energy flux) which
  - are governed by Fresnel’s principle which is mathematically expressed by ray equation.
Physical and Geometrical Optics: Unified Theory

Physical Optics

- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations.

Physical-optics generalization of geometrical optics
Example Spherical Field with Stop

\[ V_\ell(\rho, z, \omega) = |V_\ell(\rho, z, \omega)| \exp(i\varphi_\ell(\rho, z, \omega)) \exp(i\psi(\rho, z, \omega)) \]
Results of Fourier Transform

\[ V_\ell(\rho, z, \omega) = |V_\ell(\rho, z, \omega)| \exp(i\phi_\ell(\rho, z, \omega)) \exp(i\psi(\rho, z, \omega)) \]

Decreasing radius of curvature; increasing NA
Results of Fourier Transform

\[ V_\ell(\rho, z, \omega) = |V_\ell(\rho, z, \omega)| \exp(i\varphi_\ell(\rho, z, \omega)) \exp(i\psi(\rho, z, \omega)) \]

Decreasing radius of curvature; increasing NA

Mapping between both domains: geometric Fourier transform
Field Zones by Mathematical Definition

- Geometric Fourier transform valid in specified modeling accuracy
- Field on reference plane is in geometric field zone
- Rigorous Fourier transform required in specified modeling accuracy
- Field on reference plane is in diffractive field zone
Physical and Geometrical Optics: Unified Theory

- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations.
Physical and Geometrical Optics: Unified Theory

- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations
Physical and Geometrical Optics: Unified Theory

• Physical optics:
  − Light represented by electromagnetic fields which
  − are governed by Maxwell’s equations
  − Transition between diffractive/geometric branch fully specified and controlled by mathematical concept of geometric FT
Physical and Geometrical Optics: Unified Theory

- Physical optics:
  - Light represented by electromagnetic fields which
  - are governed by Maxwell’s equations
  - Transition between diffractive/geometric branch fully specified and controlled by mathematical concept of geometric FT.

Physical optics in geometric zones is at least as fast as ray tracing!
VirtualLab Fusion manages the transition between diffractive and geometric branches of physical optics automatically (steady development).
Modeling and design of beam delivery systems by physical optics
An introduction to non-sequential field tracing
Physical-Optics System Modeling: Regional Maxwell Solver

Maxwell Solver
- Lenses, …
- Prisms, …
- Gratings, …
- micro- and nano-structures
- fibers, …

Homogeneous medium, like air or vacuum
In *Fast Physical Optics* we comply with the following strategies:

1. Tearing: The optical system is decomposed into various regions in which different types of specialized Maxwell solvers are applied.
Physical-Optics System Modeling: Regional Maxwell Solver
In **Fast Physical Optics** we comply with the following strategies:

1. **Tearing:** The optical system is decomposed into various regions in which different types of specialized Maxwell solvers are applied.

2. **Interconnection:** The solutions per region are connected through non-sequential field tracing to solve Maxwell’s equations in the entire system.

---

**Non-Sequential Optical Field Tracing**

Michael Kuhn, Frank Wyrowski, and Christian Hellmann

Sequential Connection of Regional Maxwell Solver

Maxwell Solver
Lenses, …

Maxwell Solver
Prisms, …

Maxwell Solver
Gratings, …

Maxwell Solver
micro- and nano-structures

Maxwell Solver
fibers, …

Homogeneous medium, like air or vacuum
Non-Sequential Connection of Regional Maxwell Solver

Maxwell Solver Prisms, …
Maxwell Solver Continuum, …
Maxwell Solver micro- and nano-structures
Maxwell Solver fibers, …

Maxwell Solver Lenses, …

Homogeneous medium, like air or vacuum
Non-Sequential Connection of Regional Maxwell Solver

Rigorous propagation in $k$-domain:

$$\tilde{V}^{\text{out}}(\kappa, z) = \tilde{V}^{\text{in}}(\kappa, z_0) \times \exp \left( i \kappa \Delta z \right)$$
Field Tracing Operators: Space- and k-Domain

- The free-space operator equation is given by
  \[ E^{\text{out}}_\perp(\rho, \omega) = \mathcal{P} E^{\text{in}}_\perp(\rho, \omega) \]
  and in matrix form by
  \[
  \begin{pmatrix}
  E^{\text{out}}_x(\rho, \omega) \\
  E^{\text{out}}_y(\rho, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \mathcal{P} & 0 \\
  0 & \mathcal{P}
  \end{pmatrix}
  \begin{pmatrix}
  E^{\text{in}}_x(\rho, \omega) \\
  E^{\text{in}}_y(\rho, \omega)
  \end{pmatrix}.
  \]

- The free-space operator equation in k-domain is given by
  \[ \tilde{E}^{\text{out}}_\perp(\kappa, \omega) = \tilde{\mathcal{P}} \tilde{E}^{\text{in}}_\perp(\kappa, \omega) \]
  with \( \kappa = (k_x, k_y) \). In matrix form we have
  \[
  \begin{pmatrix}
  \tilde{E}^{\text{out}}_x(\kappa, \omega) \\
  \tilde{E}^{\text{out}}_y(\kappa, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \tilde{\mathcal{P}} & 0 \\
  0 & \tilde{\mathcal{P}}
  \end{pmatrix}
  \begin{pmatrix}
  \tilde{E}^{\text{in}}_x(\kappa, \omega) \\
  \tilde{E}^{\text{in}}_y(\kappa, \omega)
  \end{pmatrix}.
  \]
Non-Sequential Connection of Regional Maxwell Solver

\[ (\rho, \omega) \xrightarrow{\mathcal{F}_\kappa} \mathcal{B}_1 \xleftarrow{\mathcal{F}_\kappa^{-1}} \mathcal{F}_\kappa \xrightarrow{\mathcal{F}_\kappa} \tilde{P} \xrightarrow{\rho, t} \]
Field Tracing Operators: Space- and k-Domain

- The free-space operator equation is given by
  \[ E_{\perp}^{\text{out}}(\rho, \omega) = \mathcal{P} E_{\perp}^{\text{in}}(\rho, \omega) \]
  and in matrix form by
  \[
  \begin{pmatrix}
  E_x^{\text{out}}(\rho, \omega) \\
  E_y^{\text{out}}(\rho, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \mathcal{P} & 0 \\
  0 & \mathcal{P}
  \end{pmatrix}
  \begin{pmatrix}
  E_x^{\text{in}}(\rho, \omega) \\
  E_y^{\text{in}}(\rho, \omega)
  \end{pmatrix}.
  \]

- Analogously we have for the \( B \)-operator
  \[ E_{\perp}^{\text{out}}(\rho, \omega) = \mathcal{B} E_{\perp}^{\text{in}}(\rho, \omega) \]
  and in matrix form
  \[
  \begin{pmatrix}
  E_x^{\text{out}}(\rho, \omega) \\
  E_y^{\text{out}}(\rho, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \mathcal{B}_{xx} & \mathcal{B}_{xy} \\
  \mathcal{B}_{yx} & \mathcal{B}_{yy}
  \end{pmatrix}
  \begin{pmatrix}
  E_x^{\text{in}}(\rho, \omega) \\
  E_y^{\text{in}}(\rho, \omega)
  \end{pmatrix}.
  \]

- The free-space operator equation in \( k \)-domain is given by
  \[ \tilde{E}_{\perp}^{\text{out}}(\kappa, \omega) = \tilde{\mathcal{P}} \tilde{E}_{\perp}^{\text{in}}(\kappa, \omega) \]
  with \( \kappa = (k_x, k_y) \). In matrix form we have
  \[
  \begin{pmatrix}
  \tilde{E}_x^{\text{out}}(\kappa, \omega) \\
  \tilde{E}_y^{\text{out}}(\kappa, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \tilde{\mathcal{P}} & 0 \\
  0 & \tilde{\mathcal{P}}
  \end{pmatrix}
  \begin{pmatrix}
  \tilde{E}_x^{\text{in}}(\kappa, \omega) \\
  \tilde{E}_y^{\text{in}}(\kappa, \omega)
  \end{pmatrix}.
  \]

- Analogously we have for the \( B \)-operator
  \[ \tilde{E}_{\perp}^{\text{out}}(\kappa, \omega) = \tilde{\mathcal{B}} E_{\perp}^{\text{in}}(\kappa, \omega) \]
  and in matrix form
  \[
  \begin{pmatrix}
  \tilde{E}_x^{\text{out}}(\kappa, \omega) \\
  \tilde{E}_y^{\text{out}}(\kappa, \omega)
  \end{pmatrix} =
  \begin{pmatrix}
  \tilde{\mathcal{B}}_{xx} & \tilde{\mathcal{B}}_{xy} \\
  \tilde{\mathcal{B}}_{yx} & \tilde{\mathcal{B}}_{yy}
  \end{pmatrix}
  \begin{pmatrix}
  \tilde{E}_x^{\text{in}}(\kappa, \omega) \\
  \tilde{E}_y^{\text{in}}(\kappa, \omega)
  \end{pmatrix}.
  \]
Bidirectional Operator: k-Domain

- For the bidirectional operator in $k$-domain we can express a matrix element the integral of the form

$$\tilde{V}^{\text{out}}(k_x, k_y) = \int_{K^2} \tilde{B}(k_x, k_y, k'_x, k'_y) \tilde{V}^{\text{in}}(k'_x, k'_y) \, dk'_x \, dk'_y .$$

with the integral kernel $\tilde{B}(k_x, k_y, k'_x, k'_y)$.

- Since $\tilde{V}^{\text{in}}(k'_x, k'_y)$ can be understood as a decomposition into (inhomogeneous) plane waves, the bidirectional operator provides the plane-waves response on one incident plane wave.

- The integral operator reduces to a multiplication for stratified media and gratings per order (with $k$-value mapping).
Non-Sequential Connection of Regional Maxwell Solver

\[(\rho, \omega) \xrightarrow{\mathcal{F}_\kappa} \mathcal{B}_1 \xrightarrow{\mathcal{F}_\kappa^{-1}} (\kappa, \omega) \xrightarrow{\tilde{P}} (\rho, t)\]
Non-Sequential Connection of Regional Maxwell Solver

\[(\rho, \omega) \xrightarrow{\mathcal{F}_\kappa} \mathcal{B}_1 \xrightarrow{\mathcal{F}_\kappa^{-1}} \mathcal{F}_\kappa \xrightarrow{\mathcal{F}_\kappa} \tilde{\mathcal{P}} \xrightarrow{\tilde{\mathcal{B}}_2} (\kappa, \omega) \]

Homogeneous medium, like air or vacuum
Non-Sequential Connection of Regional Maxwell Solver

\[(\rho, \omega) \quad B_1 \quad F_{\kappa}^{-1} \quad F_{\kappa} \quad F_{\kappa} \quad F_{\kappa}^{-1} \quad (\kappa, \omega) \quad \tilde{\mathcal{P}} \quad \tilde{\mathcal{B}_2} \quad \tilde{\mathcal{P}} \quad (\rho, t)\]
Non-Sequential Connection of Regional Maxwell Solver

Characteristics of connection between the domains of utmost importance!
Modeling and Design of Optical Systems by Physical Optics

- Geometric Fourier Transform (GFT)
- Rigorous Fourier Transform (FFT)
Modeling and Design of Optical Systems by Physical Optics

- Compared to ray tracing, you do not lose anything by fast physical optics.
- Ray tracing is included in VirtualLab Fusion software on a solid base knowing about limitations of ray optics.
- By going beyond ray tracing:
  - You win more information about the light in your system.
  - You get better insight into the performance of your system.
  - You can include and investigate more effects.
  - You can model with higher accuracy.
  - You are ready for new optical design concepts and by that for innovative optical solutions.
Example

Focusing Properties inside Crystal
Many laser crystals are made out of birefringent materials whose optical properties depend strongly on the polarization of light and the orientation of the crystal.

The optic axis of the crystal is first set along the $x$ direction, then along the $y$ direction.
Field Tracing Diagram

- µm & nm structures
- crystals & anisotropic media
- SLMs/adaptive components
- nonlinear components
- free space
- Prism, cubes
- lenses
- gratings
- freeforms
- DOEs, HOEs, CGHs
- diffuser
- lens arrays
- aperture
- volume gratings
- μm & nm structures
- SLMs/adaptive components
Simulation Results

- Light distribution at different depth (o.a. along y direction)

Calculation at one depth: ~ 9 s
with Intel Core i7-4910MQ

Simulation Results

- Light distribution at different depth (o.a. along x direction)

Example

Focusing of an high-NA laser diode
What is the field in focal region behind an aspherical lens? Especially, the astigmatism of the laser diode must be taken into account.
Results – 3D Ray Tracing

• Ray tracing – system in 3D space

Ray-tracing analysis provides a fast overview of the system in space.
Results – Intensity at Focal Plane

- Field tracing

<table>
<thead>
<tr>
<th>Diameter</th>
<th>With Astigmatism</th>
<th>Without Astigmatism</th>
</tr>
</thead>
<tbody>
<tr>
<td>x direction</td>
<td>11.80 µm</td>
<td>11.41 µm</td>
</tr>
<tr>
<td>y direction</td>
<td>21.48 µm</td>
<td>19.23 µm</td>
</tr>
</tbody>
</table>

Physical-optics simulation of whole system, including collimation and focusing lenses, takes only 2 seconds!
Results – Intensity in Focal Region (without Astigmatism)

- Field tracing

Physical-optics simulation of field evaluation within focal region, over 30 steps, takes about 90 seconds.

- Field tracing

high-NA laser diode without astigmatism
Results – Intensity in Focal Region (with Astigmatism)

- Field tracing

High-NA laser diode with astigmatism

Minimum beam diameters appear at different positions along $x$ and $y$ directions, due to astigmatism of the laser diode.
Results – Beam Diameter in Focal Region

- Field tracing

quantitative measurement of the evolution of beam diameters in both directions

high-NA laser diode with or w/o astigmatism
Example

Focusing of a pulse by an off-axis parabolic mirror
Modeling Task

How to calculate output pulse in the focal plane, including the spectral / temporal profile and the spatial distribution of the focal spot for all vectorial field components?

- time duration 10 fs (FWHM)
- carrier wavelength 800 nm
- beam diameter 7 mm
- linearly polarized in x direction

input pulse

off-axis parabolic mirror
Spectral and Temporal Amplitudes at Input Plane

The linearly polarized input pulse has an $E_y$ & $E_z$ component with zero amplitude.

Simulation time ~seconds
Spectral and Temporal Amplitudes at Output Plane

Non-zero $E_y$ & $E_z$ component appears due to polarization crosstalk in high-NA focusing situation.

**Spectral Amplitude**

- $E_x$

**Temporal Amplitude**

- $E_x$
- $E_y$
- $E_z$

Simulation time ~seconds
Spatial Distribution at Output Plane

\[ |E_x|^2 @ 800\,\text{nm} = 100\% \]

\[ |E_y|^2 @ 800\,\text{nm} = 3\% \]

\[ |E_z|^2 @ 800\,\text{nm} = 4\% \]
Summary

• Fast physical optics is as fast as ray tracing (geometric zones of a system)
• Fast physical optics enables numerous innovative solutions in light shaping.
• All examples in talk were provided by VirtualLab Fusion software.
• LightTrans International: Consulting and Engineering Services

Hall 4, Booth 4B71.1