Application of Numerical Sensitivity Analyses in Advanced Optical Modeling & Design

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VirtualLab – Characterization

optical modeling, design and simulations

• predestined for complex systems which require different modeling and simulation techniques

• fast geometrical & physical optics engines
  – Ray Tracing
  – Field Tracing

• modular, intuitive graphical user interface with many assisting tools

• toolbox concept for user specific needs

• development adjusted to current needs of industry and science
VirtualLab – Typical Areas of Application

- Laser Systems and Ultra-Short Pulses
- Micro and diffractive optics freeform and gratings
- Illumination systems including functional surfaces
- Stable, unstable and ring resonators
- Imaging systems with diffractive and hybrid lenses, customized screens.
- Next version: Advanced simulation of Near Eye Display (NED) devices
Business by Applied Computational Optics

- Coherent
- Microsoft
- Apple
- Google
- Facebook
- Corning
- ...

- Schott
- Zeiss
- Jenoptik
- Trumpf
- Continental
- Bosch
- Hella
- Airbus
- Max Planck Institutes
- ELI
- ...

- Canon
- Sony
- LG
- Samsung
- Ricoh
- ...

- Huawei
- Numerous institutes and universities
- ...

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Flexibel Approach for All Kinds of Systems

different modeling techniques

including approximated & rigorous methods

Pictures from http://de.wikipedia.org/
Typical understanding and impression:

- Physical optics modeling seems to be slow and often not practical!
- Ray optics modeling is fast and practical!

Ray tracing is still used in practice in most modeling situations.
However:

• Application of Monte Carlo ray tracing for scattering and extended sources tends to be very slow!
• **Physical limitations of ray tracing has become more serious for innovative photonics products.**

Increasing demand and interest in physical optics modeling and design based on **fast physical optics**!
VirtualLab

Starting Point

Optical System to be optimized/investigated

1. VirtualLab setup / modeling / simulation of system
2. VirtualLab optimization
3. VirtualLab evaluation of optimized system

→ optimizing → evaluation
**VirtualLab + optiSLang**

*Starting Point*  
*Optical System to be optimized/investigated*

1. **VirtualLab**  setup / modeling / simulation of system  
2. **optiSLang**  high end optimization & analysis  
3. **VirtualLab**  evalulation system optimized by **optiSLang**
Example: Beam Splitter

• required for various applications, e.g. motion tracking (Microsoft Kinect), LIDAR and laser material processing

• optimization is challenging, especially for large diffraction angles (high NA)

• microstructures with structure sizes in range of wavelength
Setup & Requirements

- definition of **Total Efficiency**:
  \[ \eta = \eta_1 + \eta_{-1} + \eta_3 + \eta_{-3} + \eta_5 + \eta_{-5} > 80\% \]

- definition of **Uniformity Error**:
  \[ U = \frac{\eta_{\text{max}} - \eta_{\text{min}}}{\eta_{\text{max}} + \eta_{\text{min}}} < 0.5\% \]
Definition of Parameters & Constraints

- introduction of 6 parameters: lengths $L_1$, $L_2$, $L_3$, $L_4$, $L_5$ and $L_6$
- minimal feature size
- total length is equal to period (thus only 5 of 6 lengths are free)
- modulation depth: $zScaling$
Sensitivity Analysis

- Advanced Latin Hypercube Sampling
- 2000 designs
- input parameter:
  - $L1$–$L6$: 0…2.74 µm
  - $z$Scaling: 0.93 µm…1.14 µm
Result of Sensitivity Analysis

- 2000 designs
- only 4 results close to optimum
- reason: inadequate definition of parameters and/or objective function
Sensitivity Analysis: Parallel Coordinate Plot

- close to optimum: \( L_1/L_4 \), \( L_2/L_5 \) and \( L_3/L_6 \) correspond to each other
- therefore: reduction of parameters \( L_2=L_5 \) and \( L_1=L_2=L_3=L_4=L_6 \) and introduction of parameter FreeLength
Sensitivity Analysis: Parameter Optimization

- sensitivity analysis based on 6 parameters
- 2000 designs
- CoPs between 56% and 99%
- no influence of $z$Scaling

- sensitivity analysis based parameter $FreeLength$
- 100 designs
- CoPs 99%
- $z$Scaling shows small influence
Sensitivity Analysis: Final Dependencies

- all response strongly depend on \textit{FreeLength}
- \textit{UniformityError} is independent of \textit{zScaling}
- low noise level of VirtualLab model (less than 1%)
Sensitivity Analysis: Design Improvement

- UniformityError is independent of $zScaling$, thus only $FreeLength$ is considered in range of optimum
  → reduction of number of input parameters
- $FreeLength$ differs in optimum of $TotalEfficiency$ and $UniformityError$
  → responses are slightly in conflict
  → definition of $UniformityError$ as constraint for optimization
Optimization result

- Optimization based on Adaptive Response Surface Method (ARSM)
- *Uniformity Error* is reduced significantly

![Graph showing optimization results with data points and a line of best fit]

<table>
<thead>
<tr>
<th></th>
<th>Target Design</th>
<th>Initial IFTA Design</th>
<th>Rigorous Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Efficiency</td>
<td>maximize</td>
<td>80.9%</td>
<td>81.4%</td>
</tr>
<tr>
<td>Uniformity Error</td>
<td>&lt;=0.5%</td>
<td>6.4%</td>
<td>0.498%</td>
</tr>
</tbody>
</table>
Summary

- analysis and understanding of parameter dependencies
- identification of optimization potential
- simplification the complexity of optical optimization problems
- optimization of parameters and optical function