HOLOEYE Photonics AG

Wide-Angle Diffractive Optical Elements: From Inverse Design to Quality Control

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HOLOEYE Pioneers in Photonic Technology

Salzburg, 18./19.09.2024

EPIC EUROPEAN PHOTONICS INDUSTRY CONSORTIUM

Outline

- Short company introduction
- DOE design in the ‚TEA‘ domain
- Higher-precision modelling options – and related challenges
- Adjoint method in photonics – for binary fan-out gratings
- Visualization and interpretation of the gradient in the spatial domain
- Additional simulation options – trade-off between accuracy and speed
- Fabrication and characterization
- Conclusion and outlook

About HOLOEYE

Business Units

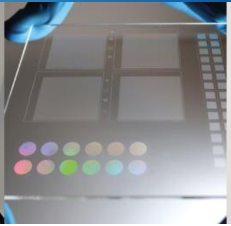
Spatial Light Modulators
Dynamic optical devices based on reflective or transmissive microdisplays for phase or amplitude modulation.

Diffractive Optical Elements
Standard components and custom design and production of Diffractive Optical Elements.

LCOS Microdisplays
LCOS microdisplays and custom display & electronics design services.

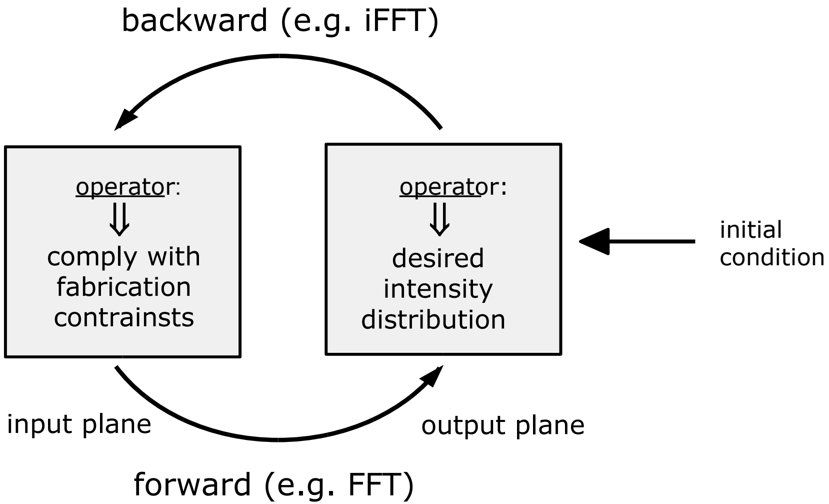
Quick Facts

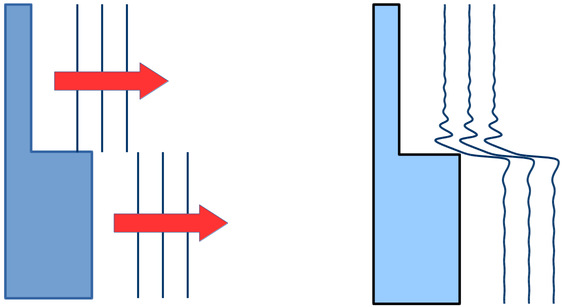
- **Head Office:** Volmerstraße 1, 12489 Berlin, Germany
- **Founded:** July 1999
- **Form of Organization:** German Aktiengesellschaft
- **Shareholders:** Privately-held company, 5 shareholders
- **Employees:** 35 – 40
- **Distributing Companies:** 10
- **Quality Management:** ISO 9001-2015


DOE design – the ‚TEA‘ domain

- TEA: ‚thin element approximation‘
- Dielectric material (glass or polymer): thickness → phase change
- Fraunhofer / Fresnel diffraction approximated by DFT / FFT
- IFTA: several stages to obtain phase-only field as ‚final solution‘





$$\Phi = \frac{2\pi}{\lambda} h \, \Delta n$$

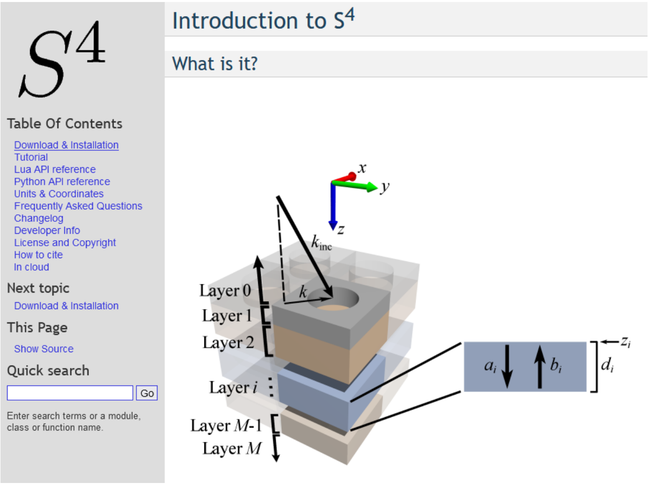
TE
RCWA, step 600nm, pixel 5µm

- *Is the prediction of what the fabricated DOE will do good enough ??*

DOE design ‚beyond TEA‘ - more precise modelling options

- Higher precision then TEA: solve Maxwell‘s equations !
- Various simulation-options for microoptical elements
  - RCWA (e.g. Synopsys DiffractMod, Lighttrans VirtualLab, S4, …
  - FDTD (e.g. Ansys Lumerical, meep, …)
  - FEM (e.g. JCMWave JCMsuite, [FreeFEM++], …)

https://github.com/NanoComp/meep/



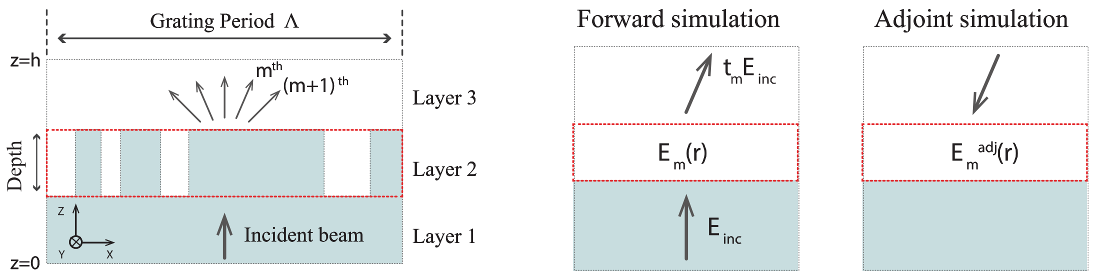
https://web.stanford.edu/group/fan/S4/

- Shared topics and issues for all mentioned methods
  1. VERY long computation times compared to TEA
  2. Algorithm(s) needed to do not only simulations, but optimizations

Disclaimer: **No recommendation for any software, in particular not one of the commercial packages. Mentioned software packages are examples only*

Adjoint method in photonics – ‚inverse design‘

- Making use of reciprocity of electromagnetic theory
- One forward and one ‚adjoint‘ simulation, e.g. 2 x RCWA
- From these two computations, a gradient ∂(FOM)/∂P can be computed
- Gradient search methods applicable
- FOM flexibility !
- Noticable similarity with IFTA with ‚variable strength projections‘



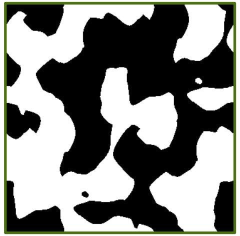
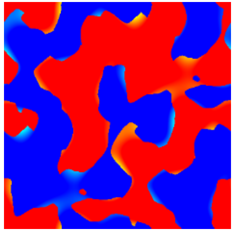
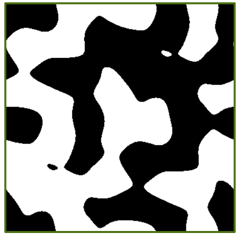
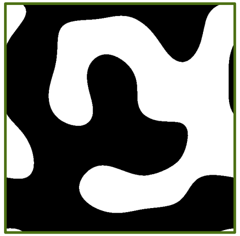
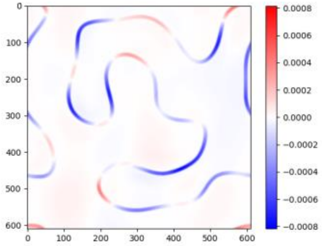
Optimization is possible for rigorous domain !

[1] C.M.Lalau-Keraly, S.Bhargava, O.D.Miller, E.Yablonovitch, 'Adjoint shape optimization applied to electromagnetic design', Opt. Express 21(18), pp 21693-21701 (2013)

[2] D.C.Kim, A.Hermerschmidt, P.Dyachenko, T.Scharf, 'Inverse design and demonstration of high-performance wide-angle diffractive optical elements', Opt. Express 28(15), p. 22321-22333 (2020)

[3] S. Bühling, F. Wyrowski, 'Improved transmission design algorithms by utilizing variable-strength projections', JOMO , Vol. 49(11), pp. 1871-1892 (2002)

Shape changes during optimization – local plots

	Unit cell DOE	Unit cell gradient		Unit cell DOE (final)	
TEA (VSP-IFTA)			→		TEA-'gradient': back-transform of change by output plane projector *modification* • *Yellow: material (red) → air (blue)* • *Light blue: air (blue) → material (red)*
Adjoint method				Gradient computed by adjoint method • *Blue and red for different signs of change: air ↔ material*	

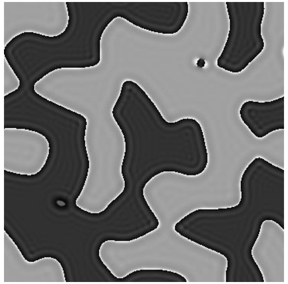
➲ Main changes during optimization for SNR or RMS: at lateral boundaries
➲ Precise fabrication of lateral shapes required !
➲ Next level of optmizations: predict proximity effects in fabrication and take them into account

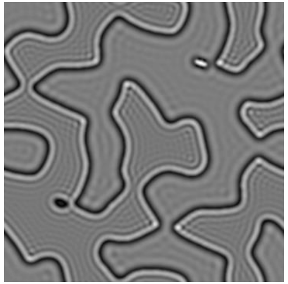
Approximate methods for larger unit cell sizes

- Computation time can still be too large
- Solutions
  a. Use more computational power
  b. Use approximations – better than TEA – faster than rigorous methods

For the second option (b.)

- Promising candidate is e.g ‚(Vectorial) wave propagation method' - WPM (Brenner1993, Fertig 2010)
- Prediction of step pertubation effects is possible
  - Considerable contribution to deviation from TEA model
  - Effects of mode-coupling not simulated, small(er) contribution for large unit cell, not ‚too small' critical dimension
- Gradient methods based on approximate methods in use @Holoeye with very good results
- Of course: whenever possible, verification by rigorous simulation (e.g. RCWA) prior to fabrication





UC of binary DOE 18µm ×18µm, λ=532nm, PMMA
Upper image: phase
Lower image: amplitude
computed by WPM

Challenges ‚beyond the design‘

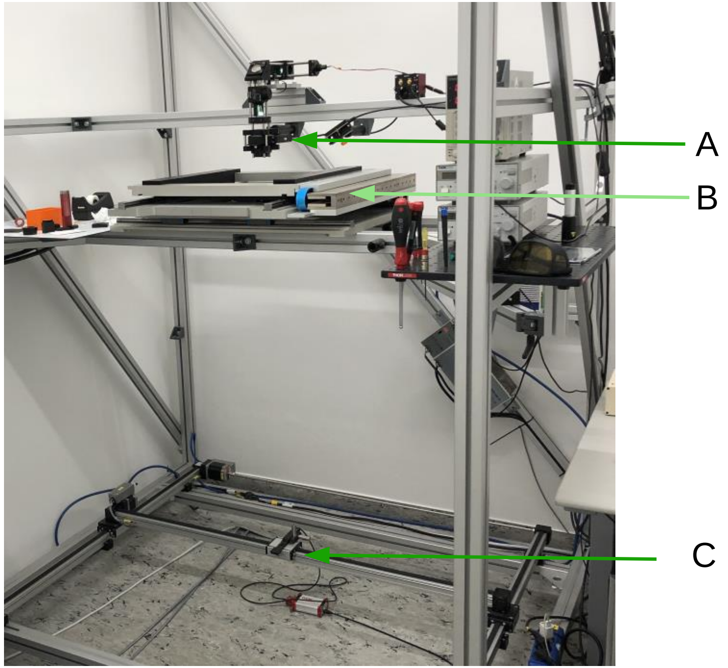
Fabrication

- ➲ Match the lateral shape
- ➲ Match the depth (typically 1-2% is good enough)

Eye safety issues arise in laser + DOE applications if shape and depth precision targets are not met.

Measurement

- ➲ Choose how to set up the testing equipment
  - ➲ Flexible measurement, e.g. based on (calibrated) power sensor(s) during development iteration(s)
  - ➲ Transfer to spectrometer-based or camera-based measurement set-ups for volume production



A-laser exit aperture, B- wafer stage, C- moveable sensor

Summary and conclusion

- ‚TEA‘ design methods often not suitable
- Rigorous methods can be used in optimizations based on the adjoint method
  - Fan-out gratings and full-pattern angle (FPA) >100° and <10% uniformity error
- Approximate methods for larger unit cell sizes
  - Unit cell sizes of a few 100µm and FPA 20° .. 40° and uniformity errors ≤5%
- Optimization options to suppress too small features
- Binary and multi-level DOE designs

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