Micro- and Nano-Technology...
... for Optics

5. Applications

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Beam Shaper and CGHs

Virtual Keyboard

3D-CGHs

… for anti-counterfeiting
**Classification**

**beam splitting**
- beam is split into a set of discrete, identical beams
- shape of the illumination beam is repeated in each split beam
- elements are typically periodic, splitted beams correspond to diffraction orders

**beam shaping**
- intensity distribution of the illumination beam is altered
- typically no replication of the illumination beam
- element is not periodic
Design Algorithm IFTA

illuminaton

search for a start phase \( T_0(x,y) \)

projection-operator (e.g. correction for \( U_b(x,y) \))

\[ T_s^{(i)}(x,y) \cdot U_b(x,y) \]

\( U_b^{(i+1)}(x,y) \)

\[ P_s[U_s^{(i)}(x,y)] \]

element plane

\( U_s^{(i)}(x,y) \)

projection-operator (e.g. intensity correction)

signal plane

signal
Beam Shaping Examples

measured surface profile
measured intensity distribution
Example: 1 – 5 Beam-Splitter

phase of a single grating period:

grating: (periodic extension

\[ \eta = 92\% \]
Example: Complex Beam Splitter

phase within unit cell:

related far-field intensity distribution:

periodic extension:
Simple 1:1 Imaging Optics

Hybrid lens

Polychromatic PSF

relative pupil coordinate

wave-front error

fieldpoint 1mm off-axis

5λ

-5λ

500nm
550nm
600nm

32µm

Achromat

Hall, Dollond: ~1750

Polychromatic MTF, field point 1mm off-axis

modulation transfer function

spatial frequency [lines/mm]

0,0
0,2
0,4
0,6
0,8
1,0

0
10
20
30
40
50

diffraction limit
bi-convex lens
achromat
hybrid lens

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Refractive-Diffractive Achromat

refractive lens

\[ n = f(\lambda) \]

diffractive lens

\[ \alpha = f(\lambda) \]

hybrid achromat
Experimental Results


diffractive-refractive hybrid lens, fabricated by specially developed Laser-lithography without correction with correction
Application Example

DUV-Microscope Objective

- extremely limited material choice for UV-achromatic lenses
- use of diffractive-refractive hybrid lens

microscope objective for $\lambda=193\text{nm}$

Quelle: Zeiss

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Binary Gratings

normal incidence

-1 0 +1

symmetric splitting in positive and negative diffraction orders

max. 50% efficiency in 1. diffraction order

tilted incidence

-1 0

breaking the symmetry

\( \frac{\lambda}{2} < p < \lambda \)

efficiencies > 95% achievable for -1. diffraction order!
Gratings for fs-Pulse Compression

Grating compressor:
- compressed Pulse
- chirped Pulse
different propagation times of different spectral components of the pulse

Efficiency:
- $\eta > 96\%$
p=700nm, $\lambda = 800\text{nm}$
- theoretical efficiency (TE-pol.)
- $97.7\%$

Efficiency: $\eta > 96\%$
Reduced Efficiency due to Fresnel Reflection

Increasing dispersion

Fresnel reflection
air - fused silica

rectangular grating

angle of incidence (Littrow)

90° 60° 50° 45° 40° 35° 30°

Reflection [%]

0 10 20 30 40

Grating period [λ]

0.5 0.6 0.7 0.8 0.9 1.0

TE-Polarization
Littrow-mounting
High Efficient Transmission Gratings

“Fabry-Perot-Cavity” for symmetric reflection at top and bottom of grating

Encapsulated Grating

Layer-Stack under Grating

Increase of efficiency (TE-pol):

\[ \text{93\%} \quad \text{99.9\%} \text{ (theory)} \quad \text{97\%} \text{ (experiment)} \]

\[ p = 600 \text{nm} \]
\[ \lambda = 1064 \text{nm} \]
\[ \alpha_{\text{Littrow}} = 62.5^\circ \]

\[ \text{efficiency [\%]} \]

\[ p = 534 \text{nm} \]
\[ \lambda = 1030 \text{nm} \]
\[ \alpha = 71.5^\circ \]
Reflection Gratings for fs-Pulse Compression

-1\textsuperscript{st} order

0\textsuperscript{th} order

grating

HR layer stack

substrate

FIB-cross section:

Example:

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>1030 nm, bandwidth: 15 nm FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating period</td>
<td>0.571 µm</td>
</tr>
<tr>
<td>Polarization</td>
<td>TE (s-polarized E-field)</td>
</tr>
<tr>
<td>Angle of incidence</td>
<td>69.41° (in air, Littrow +5°)</td>
</tr>
<tr>
<td>Diffraction order</td>
<td>-1\textsuperscript{st} order reflection</td>
</tr>
</tbody>
</table>

measured efficiency:

99.4%
Asphere Test with CGH

The principle of interferometric testing: spherical surface shapes

- perfect “retro-reflection” of the incident spherical wave (if mirror surface is perfectly spherical)
- deviations from sphere are shown in the interferogram as wave-front error

Interferogram example showing ~2λ spherical aberration
Asphere Test with CGH

**without CGH:**

- Test-beam from / to interferometer
- CGH
- Aspherical mirror

**with CGH:**

- Test-beam from / to interferometer
- CGH
- Flat wave-front
- Simple analysis

**Interferogram**

- Without CGH: with CGH:
  - To much interference fringes
  - Analysis impossible

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**Application Example**

**Example:** projection objective for DUV-lithography

9 Aspheres required wave front precision: \(< \lambda / 100\)

**Challenge:** Accuracy!
Examples – Asphere-Test CGHs

9” CGH for primary mirror of the GAIA-satellite telescope

9” CGH for secondary mirror of the METI-satellite telescope

Critical Parameters:
- size (up to 300mm in future)
- positioning accuracy
- data preparation
- homogeneity of etching depth and shape of grooves

wave-front accuracy < 3nm (rms) demonstrated
Gratings for Space Applications

Typical application: **Spectrometer**

**relevant parameters:**
- spectral resolution
- bandwidth
- efficiency
- wavefront
- straylight
- size

often extreme demands to obtain high sensitivity

Can direct-write-lithography do the job?
GAIA (ESA) launched in Dec. 2013

GAIA's effective medium grating

230mm

2μm
Das GAIA Radial Velocity Spectrometer

- the RVS is a transmission grating spectrometer located about 1m in front of the focal plane of the telescope
- red-shift registration of the „Calcium triple absorption line”
- spectral range: 847-874 nm, dispersion about 11000

Optical design
- Filter as pre-disperser
- Grating
- 2 Fery prisms
- 2 Prisms
- Mass: ~30kg
Key-Requirements for the RVS-Grating

- Operation in +1. transmitted diffraction order
- **Efficiency:** > 70% → blazed grating profile required
- Grating period: 3.31\(\mu\)m
- **Wave-front error:** < 5nm RMS (in sub-pupil)
- Polarization sensitivity:< 7%
- **Stray light requirement**
- Operation at 120K, space environment compatible
- Size: 208mm x 155mm

**We need an other solution!**

- analogue technique
  - uniformity of resist layer and profile shape is not sufficient
- binary technology
  - alignment marks not allowed
  - not simultaneously achievable with standard technologies
Scaling of the grating period

\[ p > \lambda \]

\[ p = \lambda \]

\[ p < \frac{\lambda}{2} \]

Grating equation:

\[ \sin \alpha = \frac{m \cdot \lambda}{p} \]

Effective medium:

Artificial complex index

for non-normal incidence
Alternative: Effective Index Grating…

... with varying fill factor

Problem: extreme variations of aspect ratio for a complete 2D sub-wavelength structure!
Example Design

- 5 bars
- constraints: width of bars and grooves > 150nm // last bar: no constraint
- optimization: criterion TE + TM – const |TE-TM|
  - total depth ~ 1.83 µm
  - max. efficiency ~ 85%
  - polarization: O.K.
  - boundaries: eff. ~ 75%

much too small for fabrication!
The Idea

important is the local fill-factor

x-Period

80nm

y-Period

>200nm

structuring in the 2. dimension
increase of local feature size but constant fill-factor
1D-2D Design

- 5 patches in unit cell
- constraints: width of bars and grooves > 200 nm
- optimization: criterion \( |TE - TM| \)
- total depth ~ 1.9 µm
- max. efficiency ~ 85%
- polarization: O.K.
- boundary: eff. ~ 75%

same performance, but larger feature size!
Effective Medium Grating

Fabricated by
e-beam lithography reactive ion etching in SiO2

grating size: 205mm x 155mm
grating period: 3.15µm
min. feature size: 200nm
structure depth: 1.8µm

SEM-picture of etched pattern
The Flight Model of the Grating

Efficiency measured at $\lambda=850\text{nm}$

- Average Efficiency:
  - minimum: 80%
  - maximum: 84%

Polarization sensitivity

- UZE018o_7; WL850nm; Pol (06.05.10)
- average: 1.2%
- minimum: 0%
- maximum: 5.7%

very high feature size fidelity over whole grating area
Measurement of Grating Quality

**Measurement setup:**
Grating under LITTROW mount

**Effect of stitching errors:**
Phase shift → Interferometric detection
Wave-Front Error Measurement Set-Up

- measurement wavelength: 632.8nm
- WFE of external reference mirror: ≈2nm rms

double path
transmitted wave
to interferometer

plane wave from interferometer

grating
under test

external reference mirror
(diameter 300mm)
GAIA-Flight Model: Wave-Front Accuracy

1\textsuperscript{st} diffraction order
transmitted wave-front
(tilt, defocus removed)

P-V: 81nm
RMS: 8.4nm

<table>
<thead>
<tr>
<th>PV</th>
<th>0.128 wave</th>
<th>PV</th>
<th>80.81 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>rms</td>
<td>0.013 wave</td>
<td>rms</td>
<td>8.43 nm</td>
</tr>
<tr>
<td>Power</td>
<td>-0.273 wave</td>
<td>Tilt X</td>
<td>0.56 µrad</td>
</tr>
<tr>
<td>Size X</td>
<td>158.2 mm</td>
<td>Tilt Y</td>
<td>0.79 µrad</td>
</tr>
<tr>
<td>Size Y</td>
<td>206.0 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Flight Model of the Grating

Flight Model and Spare delivered to Astrium in July 2010

230mm
High-resolution gratings by “frequency doubling”

1) E-beam lithography, Cr etching

2) Photo resist etching

Grating Period: 200nm

3) Aluminum deposition

4) Aluminum sputter etching

Grating Period: 100nm!

5) Photo resist removal

T. Weber, IAP
High-resolution gratings by “frequency doubling”

Experimental characterization:

Perkin Elmer LAMBDA 950 double beam spectrometer

Al-grating
100nm period

@ normal incidence

→ noticeable extinction ratio from the NIR down to the UV range
→ Application: UV-Polarizers

T. Weber, IAP
Example: Homogenization of LEDs

LED Characteristics:
- spatially incoherent emitter
- typical emitter size 300µm x 300µm
- spectral distribution with $\Delta \lambda_{\text{FWHM}} = 20 \ldots 100\text{nm}$
Example: Homogenization of LEDs

Design and analysis with ray-tracing:

estimation of:
- collimation lens \((f_c, \text{diameter})\)
- array-parameters \((f_a, \text{lens pitch})\)
- focusing lens parameters \((f_f, \text{diameter})\)

caused by source extension

no coherent effects!
Example: Homogenization of LEDs

Analysis with wave-optics:
consideration of the physical properties of source and microoptical elements

Effects:
• diffraction at lenslet aperture
• grating arrangement of lenslets
• spectral bandwidth of LED
• source extension
• aberrations of lenslets
Physical Reason of Inhomogeneity

intensity
phase

$F$
Physical Reason of Inhomogeneity

intensity

phase

\[ f \]

\[ f \]
Example: Homogenization of LEDs

Tandem arrangement of two arrays:

Reduction of effects caused by:
- diffraction at lenslet aperture
- source extension
- lenslet aberration

![Diagram illustrating homogenization process]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
</table>

![Graph showing relative intensity vs. y [mm]]
Application: Pocket-Beamer

- Luxeon-LEDs
- small form factor
- adapted optical components (ColorCube, pol-splitter)
- adapted objective lens

homogeneity:
better 5% p.v. over 8x10 mm²
Bio-Inspired Imaging: Facett Eyes

Apposition eye (Insects)

Function principle

- Small volume
- Large field of view (FOV)
- Small resolution

© Kirschfeld

Drosophila fly
Artificial Facette Eyes

Principle: Moiré magnifier

3D Simulation

- micro-lens array
- substrate
- light sensitive pixel
- microimage (sampling point red)
- resulting overall image

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Ultra-Slim Image Sensor

Properties:
- height: 0.3 mm
- FOV: 110° diagonal
- image size: 200 x 150 pixel
- infinite depth of focus
- overall system thickness: 1.1mm

set-up with ghost-image suppression (lens diameter approx. 50µm)

"Ultra-slim image sensor" with app.-facette eye

different test images
Laser Interferometer for MEMS-Test

3 gratings:
- incoupling
- beam-splitting
- reflection

- p=1µm
- p=1µm
- p=0.5µm
Grating Optimization Results: Incoupling Grating

Quartz, depth 1µm

Design:

+ 7% due to Fresnel reflections on back side

$\eta = 63\%$
Grating Optimization Results: Beam Splitting Grating

**Design:**

- $T_{-1,-1}$
- $T_{0,0}$
- $T_{1,0}$

**Measured efficiencies:**

- $\eta_{-1} = 27\%$
- $\eta_0 = 44\%$
- $\eta_{+1} = 27\%$
Grating Optimization Results: Retro-Reflection Grating

First grating:
- trench much too narrow
  → low efficiency
- measured: ~20%

160nm trench efficiency
measured: ~80%

200nm trench
Efficiency: > 90%
Grating Substrate 1

measured efficiencies [%]:

<table>
<thead>
<tr>
<th></th>
<th>55,98</th>
<th>55</th>
<th>55,34</th>
<th>55,85</th>
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<td>59,07</td>
<td>58,81</td>
<td>58,17</td>
<td></td>
</tr>
</tbody>
</table>

including 7% Fresnel loss at back side
Grating Substrate 2

with metal coatings

grating 2

grating 3
Assembled Laser Interferometer