Spectrometer gratings based on direct-write e-beam lithography

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10. October 2017

- Electron-beam lithography for grating fabrication
- Examples of astro-gratings:
  - CUBES UV-transmission grating
  - CarbonSat high-resolution gratings
  - Sub-\(\lambda\) structures for ultra-wide-band gratings
High Performance Applications of Gratings

Spectrometers for Astronomy and Earth Observation

Manipulation/Compression of Ultra-Short Laser Pulses

relevant parameters:
- spectral dispersion
- bandwidth
- efficiency / polarization
- wavefront
- straylight
- size, …

Sentinel 4 (ESA)

often extreme demands to obtain required performance
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Resist exposure with e-beam lithography</td>
<td>Use e-beam lithography to expose the resist.</td>
</tr>
<tr>
<td>2. Resist development</td>
<td>Develop the resist to form patterns.</td>
</tr>
<tr>
<td>3. Chromium etching (RIE)</td>
<td>Etch the chromium layer using RIE.</td>
</tr>
<tr>
<td>4. Deep etching into substrate (ICP)</td>
<td>Deep etch into the substrate using ICP.</td>
</tr>
<tr>
<td>5. Removal of Cr-layer</td>
<td>Remove the chromium layer.</td>
</tr>
</tbody>
</table>

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**Optional:** multiple iterations of the process for multi-level elements.

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**Grating Technology at the IOF**

- Resist: exposing the resist to form patterns.
- Cr-layer: chromium layer for etching.
- SiO₂-Substrate: silicon dioxide substrate.

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Gratings on dielectric layer stacks

-1st order

0th order

grating

HR layer stack

substrate

- highly efficient reflection gratings
- transmission gratings with tailored polarization properties
The Vistec SB350 OS e-beam writer

- Max. writing field: 300mm x 300mm
- Max. substrate thickness: 15mm
- Resolution (direct write): <50nm
- Address grid: 1nm
- Stitching error: <12nm P-V / <2.2nm RMS
- Placement error: <14nm P-V
- Writing strategy: variable shaped beam / cell projection

- Huge flexibility to tailor the structure parameters!
- Very fast writing process!
Key Performance: Writing Accuracy

wave-front measurement
(1µm period grating + technology, Littrow-Mount)

19mm
- 6.3nm

50mm
- 6.6nm

<table>
<thead>
<tr>
<th>wavefront</th>
<th>placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>&lt;10.3 nm</td>
</tr>
<tr>
<td>rms</td>
<td>&lt;1.1 nm</td>
</tr>
</tbody>
</table>

Applications requiring this accuracy
- Asphere-Test CGH
- Puls compression gratings
- Spectrometer gratings (space application)
Accuracy of writing process: straylight

Optimization of e-beam writing process

BSDF of -1st DO:
51526 sr⁻¹

reflex from substrate

conventional e-beam writing process

optimized writing process → significant reduction of peak number and intensity

FIMAS EBB

conventional e-beam writing process

optimized writing process


given by the peak number and intensity reduction in the optimized writing process compared to the conventional one.
Examples of realized spectrometer gratings
CUBES – UV Transmission Grating

➤ CUBES (Cassegrain U-Band Brazilian ESO-Spectrograph)

➤ Requirements:
  • spectral band: 300nm – 400nm
  • line density: 3448 lines/mm → p=290nm
  • AOI: 31°
  • grating size: 250 x 250 mm²; mosaic of 2x [250mm x 130mm]

➤ Challenges:
  • commercial VPH gratings difficult in the UV

➤ Solution:
  • Binary fused silica gratings
**ESO Cubes Spectrometer**

Grating parameters:
- **wavelength:** 300nm ... 400nm
- **period:** 290nm

*SiO$_2$-option:*
- 706nm
- 100nm

*ALD-option:*
- 526nm
- 221nm

![Graph showing efficiency vs. wavelength for different options](image)

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Atomic-Layer-Deposition (ALD)

- precursor pulse 1
- purge
- repeat ALD cycles N times

- surface activated chemical reactions
- **conformal overcoating** of surface reliefs
- large number of materials possible, e.g. TiO$_2$, Ta$_2$O$_5$, Al$_2$O$_3$, HfO$_2$ ...
CUBES – UV Transmission Grating

realized grating during efficiency measurement

grating size: 250mm x 130mm
Tiling for Larger Gratings

active alignment for wave-front optimization

→ also possible for transmission gratings

arrangement of 2 reflection gratings (420mm x 210mm)
Carbon Monitoring Satellite (CarbonSat)

instrument concept:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NIR</th>
<th>SWIR-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
<td>747nm ... 773nm</td>
<td>1590nm ... 1675nm</td>
</tr>
<tr>
<td>grating period</td>
<td>423nm</td>
<td>991nm</td>
</tr>
<tr>
<td>angle of incidence to the grating (equivalent in air)</td>
<td>63.6°</td>
<td>55.5°</td>
</tr>
<tr>
<td>mean angle of diffraction</td>
<td>Transmission Gratings in -1. order Littrow configuration</td>
<td></td>
</tr>
<tr>
<td>Angular dispersion</td>
<td>0.3° / nm</td>
<td>0.1°/nm</td>
</tr>
<tr>
<td>polarization avg. efficiency</td>
<td>&gt;70%</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>polarization sensitivity</td>
<td>&lt;10%</td>
<td>&lt;10%</td>
</tr>
</tbody>
</table>
NIR – High Resolution Transmission Grating

(a) Groove depth: 2.550nm

(c) High index coating (TiO₂)

(b) Diffraction efficiency [%]

(d) TE/TM
NIR – High Resolution Transmission Grating

use high-refractive-index (dielectric) coating to reduce depth
Optical Performance

NIR-grating

AOI: 64°

SWIR-1-grating

AOI: 55°
Direct Glass-to-Glass Bonding

Advantages:

- adhesive free glass-to-glass connection
- no additional optical interface

- achieved alignment accuracy: 0.25mrad (< 1 arcmin)
- bond strength up to 2/3 of bulk fused silica
- current TRL: 6
Wide-Band Gratings

- typical requirements for a low-resolution, broad-band disperser
  - spectral range: several 100nm
  - AOI: near-perpendicular incidence
  - period: few µm

- blazed-grating in low order (saw-tooth profile)

\[\text{Blaze-Grating}\]

\[\text{efficiency vs. wavelength [nm]}\]
**Echelle or Echellette Structures**

1. Electron Beam Lithography
2. Ion Beam Etching of Mask
3. Wet Chemical Etching of Silicon

„Blaze Angle“ can be adjusted by crystalline orientation of Silicon substrate.
Echelle or Echellette Structures

period = 30µm

period = 2µm

also lower line densities possible

integrated cross-dispersion grating by direct-write structuring
Alternative: Effective Index Gratings

→ sub-wavelength pattern with varying fill factor

blazed grating → local effective index

Ph. Lalanne et al. 1998

Advantages:
only one lithography step
tailoring of dispersion properties
Effective Medium Gratings

FLEX (fluorescence explorer); [500nm – 800nm]

GAIA (global astrometric interferometer for astrophysics); [750nm – 800nm]
Wide-Band Reflection Grating

- **typical requirements**
  - based on a concave grating
  - spectral range: **340nm – 1050nm**
  - AOI: 0.5°
  - period: 30µm

- **effective medium approach**

![Diagram of a grating structure with labels for pillars, air voids, bulk, Al₂O₃ (30nm), SiO₂, aluminum, and a side view of 30µm.](image)

![Graph showing TE and TM diffraction efficiency vs. wavelength.](image)
Wide-Band Reflection Grating …

… realized by E-beam lithography

measured diffraction efficiency:

including reduced UV reflectivity of Al-layer

→ very weak spectral dependency of diffraction efficiency
Summary

- Direct write electron-beam lithography has a huge potential for the realization of high-performance gratings

**Sub-period engineering by combining E-Beam lithography and Atomic-Layer-Deposition**

To make use of the large flexibility and the advantageous optical properties requires talking with the grating manufacturer already during the design of the instrument !!! (not after PDR...)

- Examples are:
  - high resolution gratings with low polarization sensitivity
  - echelle-type gratings with integrated cross-disperser
  - ultra-wide-band gratings for lower resolution spectrometers