Analog Diffractive Optics on Flat and Non-Flat Substrates: Electron-Beam Fabrication and Applications

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I. JPL E-beam capabilities
II. Fabrication of analog-relief diffractive optical elements
III. Blazed grating on-flats substrates
   - Compact imaging spectrometers
IV. Computer-generated holograms
   - Transient-event imaging spectrometers
V. Beam-shaping diffractive optics
   - Particle velocity/flow characterization
VI. Gray-scale occulting pots
   - Coronagraphs for Terrestrial Planet Finder
I. Electron-Beam Lithography at JPL

**JEOL JBX-9300FS**

Currently the most advanced E-beam lithography system (EBLS) in the world.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JEOL JBX-9300FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>100 kV</td>
</tr>
<tr>
<td>Minimum Spot Size</td>
<td>4 nm</td>
</tr>
<tr>
<td>Beam Current for:100 nA</td>
<td>175 nA</td>
</tr>
<tr>
<td></td>
<td>10 nA</td>
</tr>
<tr>
<td>Field Size</td>
<td>500 μm</td>
</tr>
<tr>
<td>Pattern Generator Speed</td>
<td>25 MHz</td>
</tr>
<tr>
<td>Field Stitching Accuracy</td>
<td>20 nm</td>
</tr>
<tr>
<td>Write Area</td>
<td>9 in sq</td>
</tr>
<tr>
<td>Wafer Size</td>
<td>12 ind ia</td>
</tr>
<tr>
<td>Writing Grid</td>
<td>1 nm</td>
</tr>
<tr>
<td>Electron Source</td>
<td>ZrO/W Field Emission Gun</td>
</tr>
<tr>
<td>Deflection System</td>
<td>Dual Deflector</td>
</tr>
<tr>
<td></td>
<td>Low-speed 1 9-bit DC</td>
</tr>
<tr>
<td></td>
<td>High-speed 1 2-bit AC</td>
</tr>
<tr>
<td>Fine-Pitch Control</td>
<td>±5%</td>
</tr>
<tr>
<td>Height Control</td>
<td>White-light measurement</td>
</tr>
<tr>
<td></td>
<td>Auto-correction direct-write, ±0.2 mm</td>
</tr>
<tr>
<td></td>
<td>Manual via Job deck, ±2 mm</td>
</tr>
<tr>
<td>Cabling</td>
<td>Ethernet</td>
</tr>
<tr>
<td>Computer Control</td>
<td>Local Smarts - 3ln ternal</td>
</tr>
<tr>
<td></td>
<td>DECAIp haC PUs</td>
</tr>
</tbody>
</table>

**JEOL JBX-9300FS**
II. E-Beam Fabrication of Analog-Relief Diffractive Optics
**Fabrication Method**

- Thin film of e-beam resist (PMMA or PMGI) spun on substrate.
- Direct-write analog-dose electron-beam lithography.
- Electron beam breaks bonds in the resist, increasing solubility to developer.
- Developer etches exposed resist to produce surface relief pattern.
- Transfer of patterns into substrate is possible but difficult.

**Advantages**

- Well controlled analog depth (< 5% error).
- Arbitrary patterns.
- Excellent feature alignment (stitching).
- Prototype elements are efficiently fabricated.

**Diagram**

- Thin film of E-beam resist on substrate.
- Dwell Time with 50/100 keV electrons.
- After resist development.
- After transfer etching (if required).
**Pattern Preparation**

1. Desired surface relief patterns represented as square pixels (50 nm - 2.5 μm yp.)
2. Pixel depths are converted to E-beam doses using the measured nonlinear dose response of PMMA.
3. Fourier deconvolution is used to compensate the pattern for the backscattered electron dose "proximity effect" (~1/3 of the total dose, 1/e Gaussian radius ~ 10 μm).

### Nonlinear Depth vs. Dose Response of Resist

Model: $A + B \times [\exp(dose/C) - 1]$

- $A = 0.03646, 0.01423$
- $B = 0.22336, 0.01937$
- $C = 63.58254, 2.15118$

### Depth Cross-Section of a Uniform Dose Rectangle

- Center fit of CGPROX8, PF1: Dose = 100, Strength = 0.73, Range = 8.6 microns
Microlenses can improve the fill factor of focal plane array (CCDs, MOS active pixel sensors)

- Lenses fabricated by direct-write electron-beam lithography in PMMA on thin quartz substrate
- Lenses ray-aligned and bonded to detector

Surface Profile of Microlens Array

Focal plane array with 100% fill factor

Section Analysis

Horiz 9.563 μm Desired
Vert 2.065 μm 2.01
Angle 12.193 deg
Quantum well infrared photodetectors (QWIPs) require that light propagate parallel to quantum well layers to be absorbed.

Pyramid structures reflect incident light horizontally inside pyramids.

Achromatic random reflectors are designed to have zero normal-incidence reflectivity at wavelengths.
Computer-Generated Holograms

E-Beam Written Surface-Relief Phase Hologram

Incident Laser Beam

High-Contrast Gray-Scale Image

Example CGH Surface Profile (AFM Image)

Spot Arrays

Gray-Scale Images
III. Blazed Gratings on Non-Flat Substrates

*Application: Compact imaging spectrometers*

*Collaborator:*
Pantazis (Zakos) Mouroulis (JPL Section 387)
**Imaging Spectrometry**

1. Measure the spectra of all pixels in a scene
2. Analyze the spectra to obtain useful information about the scene

**Applications**

- **Remote Sensing**
  - Mineral exploration
  - Hazardous waste monitoring
  - Crop/forest health
  - Fire/Wetlands monitoring
- **Defense**
  - Target identification
  - Chemical warfare warning
- **Biology/Medicine**
  - Abnormal tissue identification
  - Fluorescence studies of cellular processes

**Slit Imaging Spectrometer**

- Spectrometer measures spectra for all points along a slit. System mounted on a scanning platform (aircraft or spacecraft) to collect spectra for a 2D area ("pushbroom scanning")

AVIRIS data (3IfC uprite, Nevada)
Need for Non-Flat Blazed Gratings

Slit imaging spectrometer based on the offner concentric w/o-mirror design

- Can be designed to have very low slit-image distortion
  - Minimizes pixel crosstalk
  - Greatly simplifies calibration of the spectrometer

- Can be very compact and lightweight

- Requires a convex grating (blazed for high efficiency)
**Convex Grating Fabrication**

- Pattern is broken into annular sections that cover equal heights steps of ~500 microns (E-beam depth of field)
- E-beam focus, deflection gain, and rotation are corrected for each annular pattern

Single blazed grating on aluminum substrate for NASA New Millennium EO-1 Mission

- Selected overdiamond ruled and holographic gratings based on measurements of efficiency, scattering, and wavefront quality
Typical Convex Grating Specifications

- TRW Hyperion (onboard NASA New Millennium EO-1 spacecraft)
- Spectrometer 1 and Spectrometer 2

### Specifications and Performance of Light-Instrument Gratings

<table>
<thead>
<tr>
<th>Grating</th>
<th>Diameter</th>
<th>Period</th>
<th>Blaze Angle</th>
<th>Substrate Sag</th>
<th>Wavelength range (order)</th>
<th>Peak Efficiency(^{\dagger}), Wavelength (order)</th>
<th>Ghosts, Scatter(^{\ddagger})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperion VNIR</td>
<td>14 mm</td>
<td>17.4 (\mu)m</td>
<td>0.55 deg</td>
<td>0.23 mm</td>
<td>0.4 – 0.85 (\mu)m (-1)</td>
<td>92% @ 490 nm</td>
<td>0.025%</td>
</tr>
<tr>
<td>Hyperion SWIR</td>
<td>14 mm</td>
<td>17.4 (\mu)m</td>
<td>2.27 deg</td>
<td>0.23 mm</td>
<td>1.13 – 2.55 (\mu)m (-1)</td>
<td>92% @ 1450 nm</td>
<td>0.16%</td>
</tr>
<tr>
<td>Spect. 1 Dual-band</td>
<td>29 mm</td>
<td>35.7 (\mu)m</td>
<td>1.19 deg</td>
<td>1.27 mm</td>
<td>0.5 – 0.85 (-2) 1.0 – 2.45 (-1)</td>
<td>91% @ 0.63 (\mu)m (-2) 93% @ 1.26 (\mu)m (-1)</td>
<td>0.05%</td>
</tr>
<tr>
<td>Spect. 2 MWIR</td>
<td>36.6 mm</td>
<td>103.6 (\mu)m</td>
<td>1.12 deg</td>
<td>0</td>
<td>3 – 5 (\mu)m (-1)</td>
<td>Not Meas.</td>
<td>Not Meas.</td>
</tr>
</tbody>
</table>

\(^{\dagger}\) - relative to an aluminum mirror

\(^{\ddagger}\) - compared to the brightest order at 633 nm, in all cases ghosts dominated over diffuse scatter

- Just delivered: 4 gratings for the APL CRISM spectrometer (Mars Reconnaissance Orbiter)
Convex Grating Diffraction Efficiency

Spectrometer 1G rating (1st Order)

- P polarization
- S polarization

Wavelength (nm)

Spectrometer 1G rating (2nd Order)

- 2nd eff (p)
- 2nd eff (s)

Wavelength (nm)
Dual-Blaze Convex Gratings

- Constant period over entire area
- Two blaze angles:
  - Center circle blazed for visible
  - Outer annulus blazed for infrared
- High efficiency for both visible and infrared
- Provides flat and high signal to noise ratio.

AFM profile of a dual-blaze convex grating showing blaze-angle zone boundary

- Average-depths area signed to minimize optical abberation at boundary
IV. Computer Generated Holograms

Application: Transient-event imaging spectrometers

Collaborators:
Greg Bearman (384)
Profs. Michael Descour and Eustace Dereniak (U. Arizona)
Computed-Tomography Imaging Spectrometer (CTIS)

Novel instrument that enablestransient-event ultispectralimaging by capturing spatial and spectral information in a single snapshot, within moving parts.

- Initial demonstration by M.D. Escour and E. Dereniak, University of Arizona

Diagram:
- Image of Scene
- Focal Plane Array Camera
- Black and white focal plane array (FPA) camera
- Captures the scene's dispersed spatial-spectral information in a single snapshot without the need for scanning

Diagram:
- 2D Grating Disperser
- Computer-generated hologram (CGH) 2D grating inc moving
- Enters the relay system, splitting the scene into multiples pectrally-dispersed images.

- Tomographic reconstruction computations yield the spectrum for every pixel in the scene
E-beam exposure and acetone development creates surface relief pattern.

Film thickness variation causes transmitted light to be diffracted into a 2D pattern.

JPL's diffractive optics fabrication and design techniques enable high performance CTIS operation.

Grating was designed to produce a 5x5 array of orders.

Fabricated grating demonstrated equal intensity orders, balanced color dispersion, and high efficiency.
Scenecom posed of LEDS and laser spots

Image captured by CTIS focal plane array (dark ambient)

Tomographic reconstruction algorithm

Spatial-spectral information in the scene

64 x 64 Panchromatic Image

Pixel Spectra (32 bands, 10.0 nm/band)
Portable CT IS System

Spinning Laboratory Target

62 x 72 Spectrally Classified Image

Common Spectra of Bright Pixels

Wavelength (nm)

Intensity
CTIS Measurements of Calibrated Reflectance Targets
(PfizerApogeeAP 9ECamer a)
V. Beam-Shaping Diff ractive Ele ments

Application: Particle velocimetry / flow characterization

Collaborators:
Prof. M ory Gharib (Caltech)
D. Modarress, D. Fourguette, et al. (V ioSense C orp.)
Diverging-Fringeshear-StressSensor

Top SideChromepattern
(slitsandin dow)

BackSideDiffraactiveOptics
(dual-linefocuslens,isolationslot,receiverlens)

PackagedSensor

150 μm from surface
50 μm from surface
Slits
Two-Spot Velocimeter

Beam-Shaping DOE Phase Map (without lens phase function)

Fabricated DOE (including lens phase function)

Simulated Intensity

Packaged "MicroV"

Measured Intensity

- Can be designed to produce arbitrary shape diffraction-limited patterns

**Status**
- Two-spot velocity sensor has been fabricated, packaged, and tested
- Scattered signal-to-noise ratio was greater than 50
VI. Gray-Scale occulting spots

*Application:* Coronagraphs for Terrestrial Planet Finder
*(Goal is to image planets around nearby stars)*

*Collaborators:*
John Trauger (JPL Section 3262), Tony Hull (JPL Section 387)
Occulting Spots in H EBS Glass

- Coronagraph designs for TPF require gray-scale occulting spots to reduce diffraction in the planetary region around the star.
- Spot must be extremely dark at center (optical density > 8, transmittance < 10^{-8}).
- Canyon Materials makes H EBS (high energy beam sensitive) glass that grays with E-beam exposure.

**Special Thick Layer HEBS G185, 100kV Exposure**

```
<table>
<thead>
<tr>
<th>Dose (μC/cm²)</th>
<th>Optical Density at 785 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00399 ± 0.00036</td>
</tr>
<tr>
<td>500</td>
<td>5.0596E-8 ± 2.1774E-8</td>
</tr>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
</tr>
</tbody>
</table>
```

Data: Data1_B
Model: H EBSSAT: $y = Ax(1+Bx^2)$
Chi^2 = 0.0017
A = 0.00399 ± 0.00036
B = 5.0596E-8 ± 2.1774E-8
- Differences between design and measured transmittance are due to E-beam proximity effect.
- We hav shown that the actuated far field oximity effect in HEBF.
- New proximity-corrected spots have been fabricated and are undergoing testing.
## Analog Surface-Relief E-Beam Fabrication Capability

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel sizes</strong></td>
<td>0.1 to 2.5 μm</td>
</tr>
<tr>
<td><strong>E-beam dose(s)</strong></td>
<td>1024</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>At least 8 microns</td>
</tr>
<tr>
<td></td>
<td>&lt;5% accuracy, typical</td>
</tr>
<tr>
<td><strong>Non-flatsubstrate sag</strong></td>
<td>3.5 mm maximum</td>
</tr>
<tr>
<td><strong>E-beam writing time</strong></td>
<td>~1 hour/cm² of area</td>
</tr>
</tbody>
</table>