Electron-Beam Fabrication of Analog-Relief Diffractive Optics on Non-Flat Substrates at Jet Propulsion Laboratory

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Outline

- Introduction
- E-beam fabrication of analog-relief diffractive optical elements
- Fabrication of blazed gratings on convex substrates
- Summary

JPL E-Beam System Specifications

Parameter	***Old → JEOL JBX-5D2***	***New → JEOL JBX-9300FS***	
Voltage	50 kV	100 kV	50 kV
Minimum Spot Size	8 nm	4 nm	7 nm
Beam Current for: 100 nm spot	10 nA	175 nA	125 nA
10 nm spot	10 pA	10 nA	4 nA
Field Size	80 μm	500 μm	1000 μm
Pattern Generator Speed	2 MHz	25 MHz	
Field Stitching Accuracy	75 nm 3σ	20 nm 3σ	
Write Area	5 in sq	9 in sq	
Wafer Size	5 in dia	12 in dia	
Writing Grid	25 A	10 A	
Electron Source	LaB_6	Field Emission Gun	
Cabling	Multiconductor Cables	Ethernet	
Control	OEM Interface to PDP11/84, VAX	Local Smarts - 3 Internal DEC Alpha CPUs	

Advantages of New System

- 10x Faster Throughput
- One Half Minimum Spot Size
- 2.5 Times Larger Wafers, 1.8 Times Larger Masks
- 3 Times Better Overlay Precision

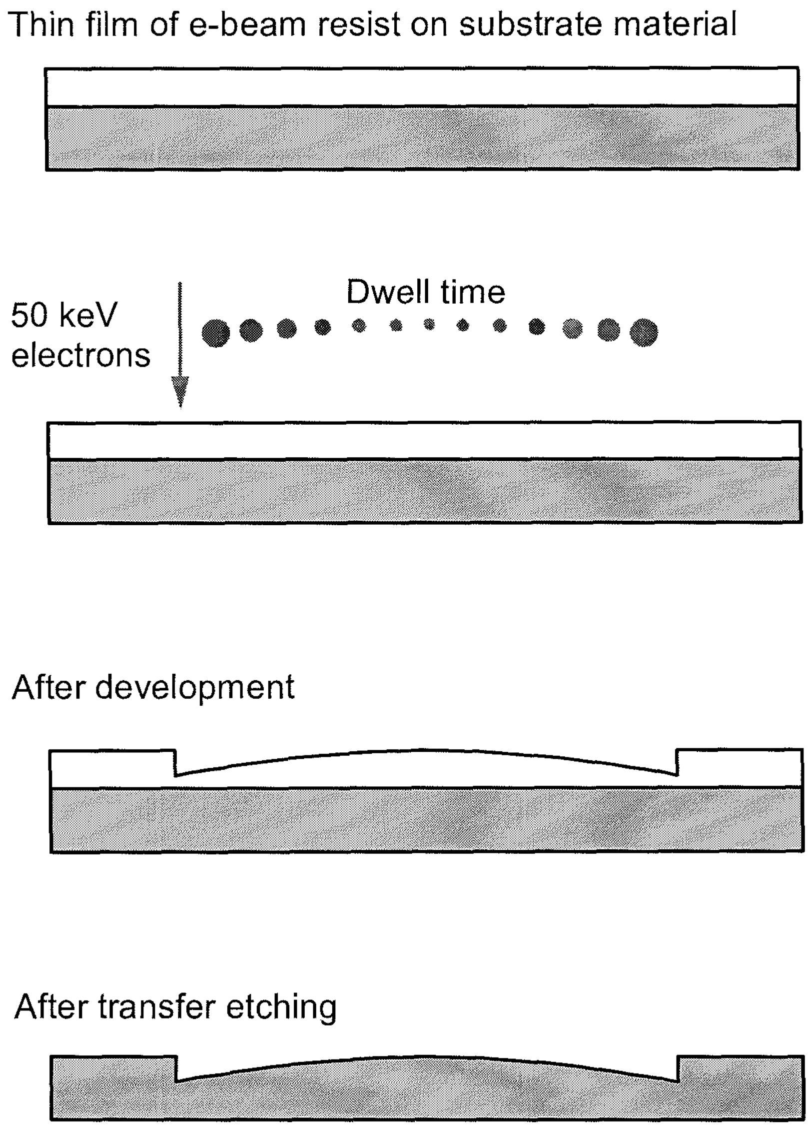
E-Beam Fabrication of Analog Diffractive Optics

Fabrication Method

- Thin film of e-beam resist (PMMA or PMGI) spun on substrate
- Direct-write analog-dose electron-beam lithography using JEOL JBX-5DII (50 kV)
- Electron beam breaks bonds in the resist - increases solubility to developer
- Developer etches exposed resist to produce surface relief pattern
- Transfer of patterns into substrate is possible if needed

Advantages

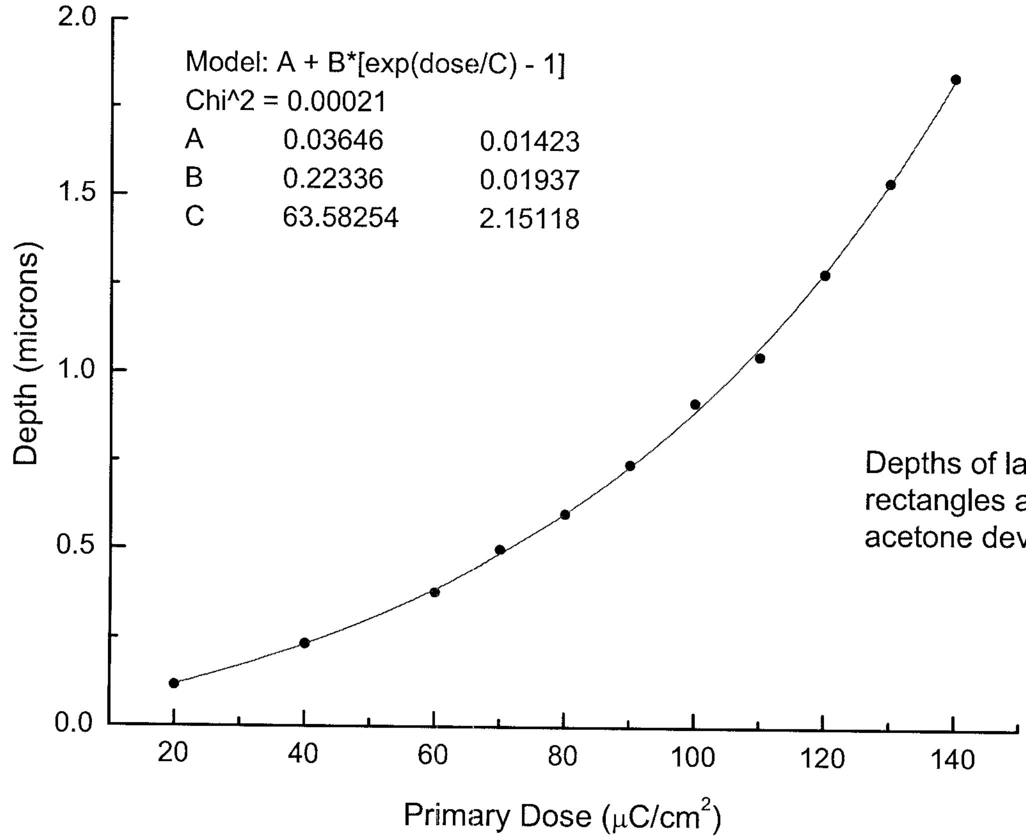
- Well controlled analog depth (< 5% error)
- Arbitrary patterns
- No pattern misalignment
- Prototype elements are efficiently fabricated



E-Beam Pattern Preparation

- Desired surface relief pattern is represented as square pixels (0.025 - 2.5 microns)
- Pixel depths are converted to E-beam doses using the measured nonlinear dose response of PMMA

$$depth = A + B[\exp(dose/C) - 1], \quad dose = C\ln\left(\frac{depth - A}{B} + 1\right)$$



Depths of large-area uniform-dose rectangles after 10 seconds of acetone development

E-Beam Pattern Preparation (continued)

- Proximity effect (dose due to back-scattered electrons) causes neighboring pixels to contribute dose to each other

$$D_{\text{total}}(\mathbf{r}) = D_{\text{primary}}(\mathbf{r}) \otimes PSF(\mathbf{r})$$

$$PSF(\mathbf{r}) = \delta(\mathbf{r}) + \frac{\eta}{\pi\alpha^2}\exp(-r^2/\alpha^2)$$

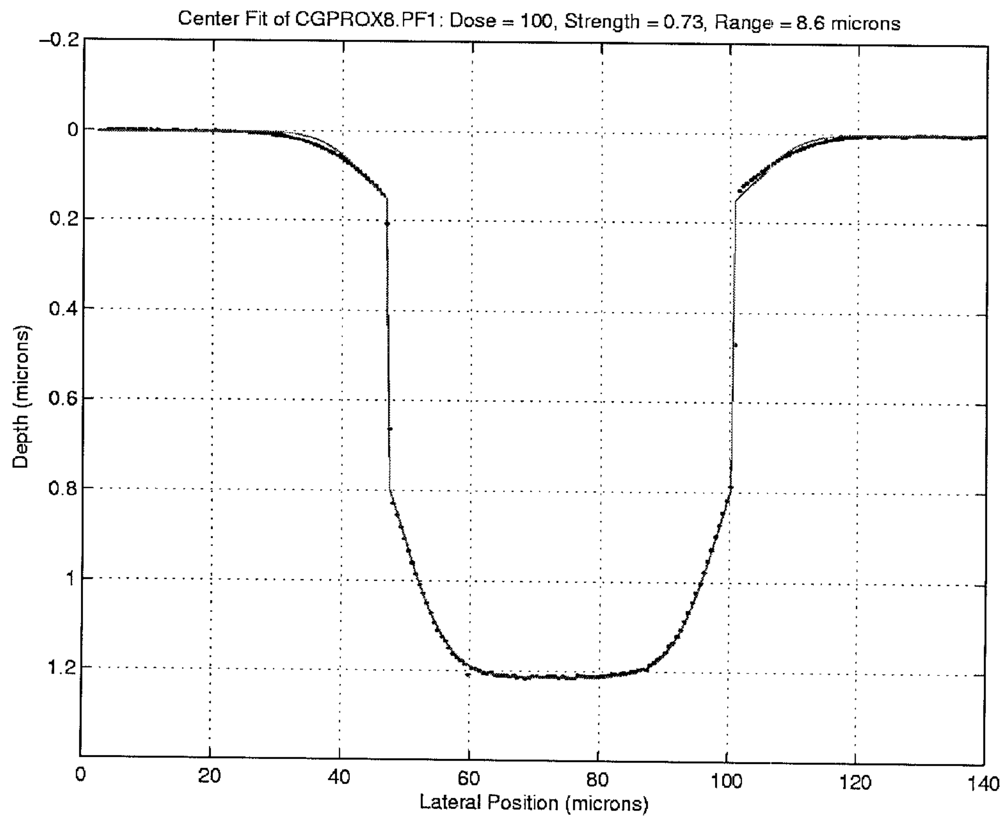
- Fourier deconvolution is used to correct pixel doses so they produce desired total dose

$$D_{\text{primary}}(\mathbf{r}) = F.T.^{-1}\left\{\frac{F.T.\{D_{\text{total}}(\mathbf{r})\}}{F.T.\{PSF(\mathbf{r})\}}\right\}$$

E-Beam Proximity Effect Measurement

- Uniform-dose rectangles are developed for 10 seconds in pure acetone then profiled with an atomic force microscope (AFM)
- Depth profiles are fit with analytical convolution of rectangle with PSF to yield strength η and range α

$$D_{tot} = D_p \,\mathrm{rect}\left(\frac{x}{w}\right) + D_p \frac{\eta}{2}\left[\mathrm{erf}\left(\frac{x+w/2}{\alpha}\right) - \mathrm{erf}\left(\frac{x-w/2}{\alpha}\right)\right], \qquad depth = A + B\left[\exp\left(\frac{D_{tot}}{C(1+\eta)}\right) - 1\right]$$



$$PSF(\mathbf{r}) = \delta(\mathbf{r}) + \frac{\eta}{\pi\alpha^2}\exp(-r^2/\alpha^2)$$

Substrate	Strength η	Range α (μm)
Fused Silica	0.50	10.7
Schott CG-455	0.73	8.6
GaAs	0.93	6.0
Aluminum	0.47	9.3

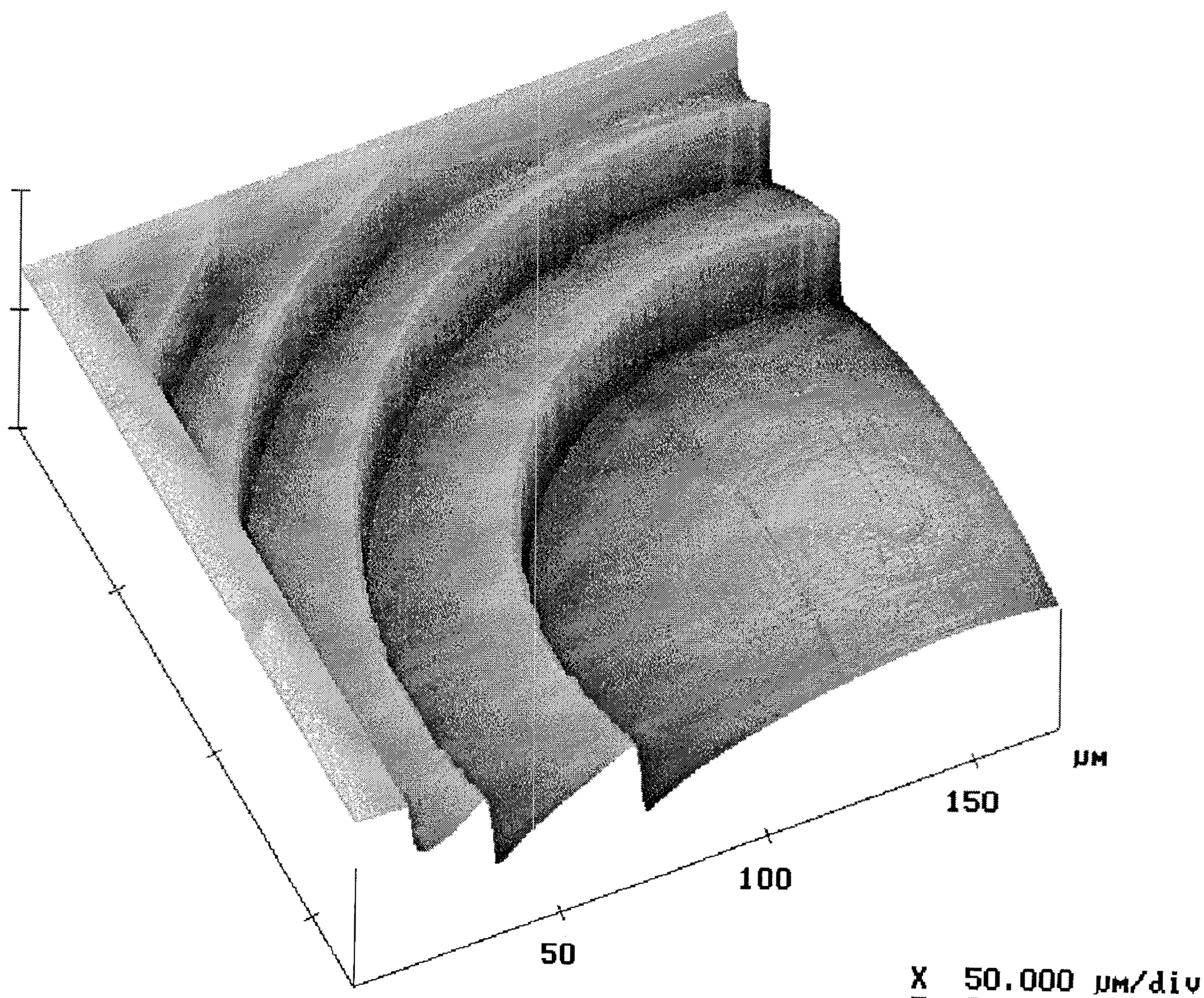
Exposure

- Blazed profiles
  - Use few E-beam spots per pixel, high current
  - Example: 1.2 micron pixels: 3x3 spots/pixel, 40 nA - **0.7 hrs/cm^2**
- Sharp-edged pixels
  - Use multiple E-beam spots per pixel, low current
  - Example: 2 micron pixels: 10x10 spots/pixel, 9 nA - **7 hrs/cm^2**

Development

- Iterative, with measurement in-between development steps
- Reflective optics
  - Surface profile measurement
- Transmissive optics
  - CGH that produces null zeroth order at correct depth

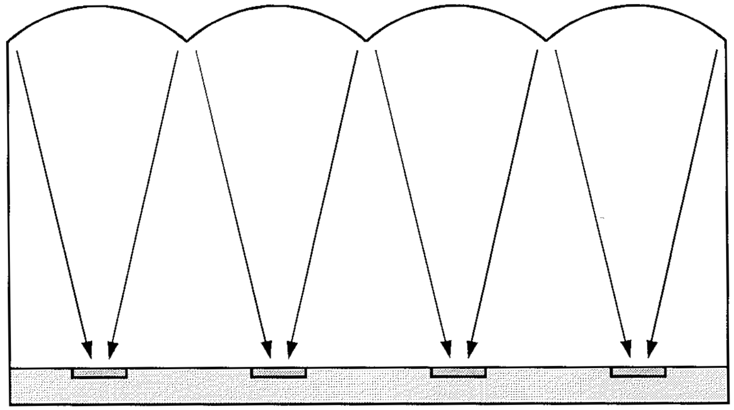
Analog Fresnel Lenses



Microlenses for Focal Plane Arrays

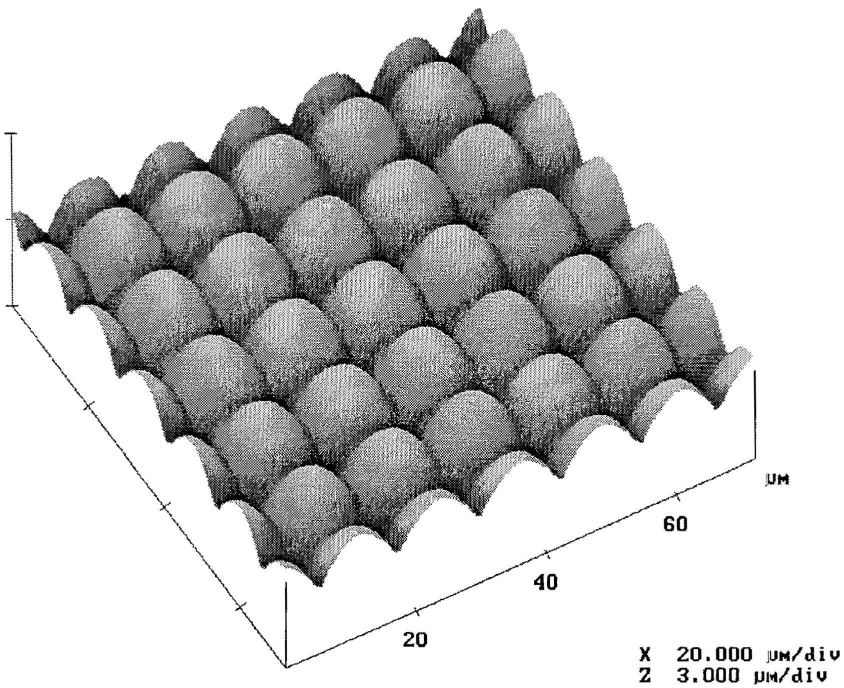
- Microlenses can improve the fill factor of focal plane arrays (CCDs, CMOS active pixel sensors)
- Lenses fabricated by direct-write electron-beam lithography in PMMA on thin quartz substrate
- Lens array aligned and bonded to detector

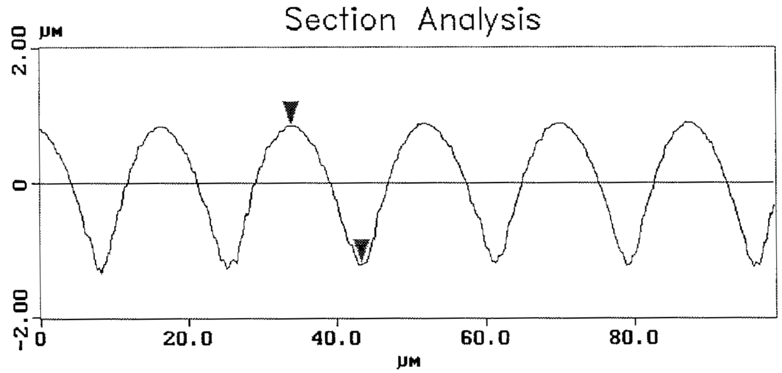
Microlens Array

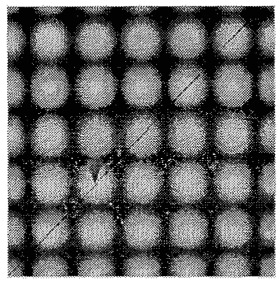


Focal plane array with < 100% fill factor

Surface Profile of Microlens Array



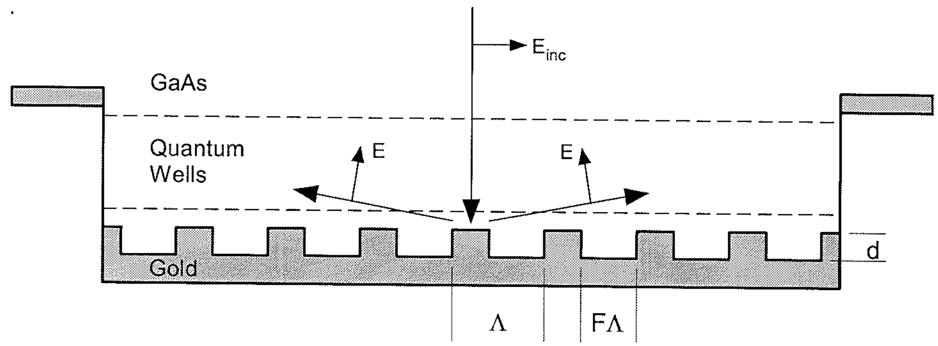




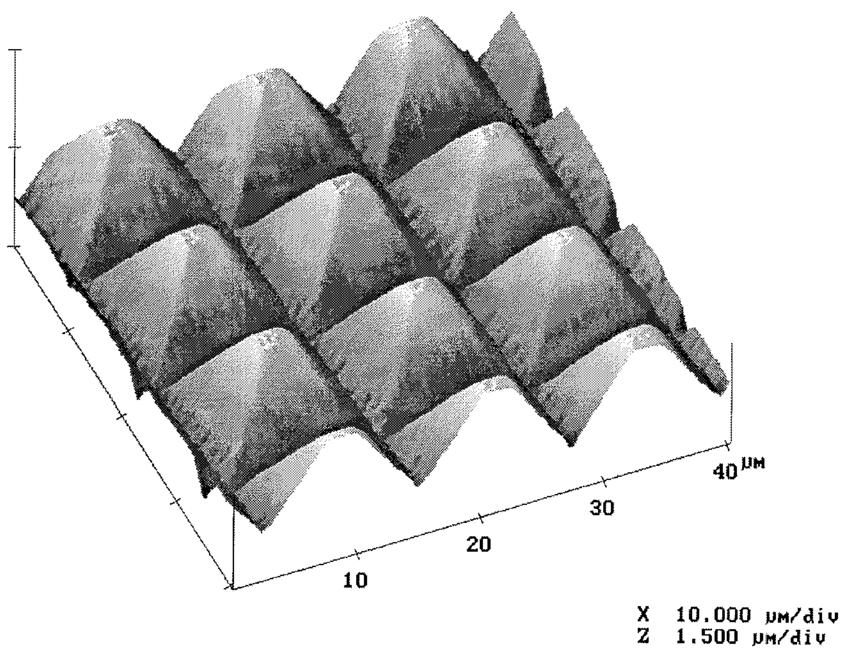
Horiz	9.563 µm	Desired
Vert	2.066 µm	2.01
Angle	12.193 deg	

Optical Coupling Structures for QWIPs

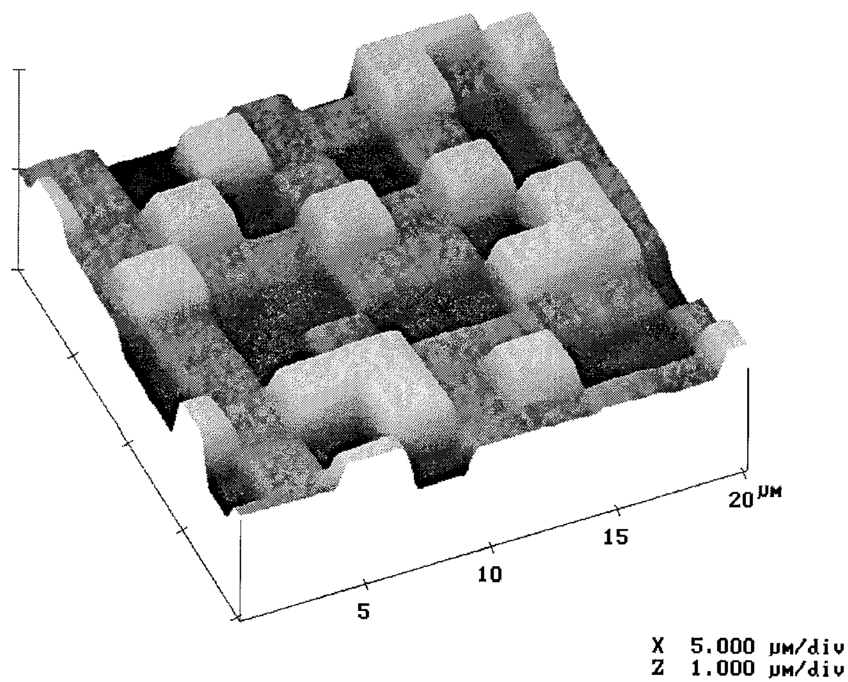
- Quantum well infrared photodetectors (QWIPs) require that light propagate parallel to quantum well layers to be absorbed



Pyramid structure reflects incident light horizontally inside pyramids



Achromatic random reflector is designed to have zero normal-incidence reflectivity at 2 wavelengths

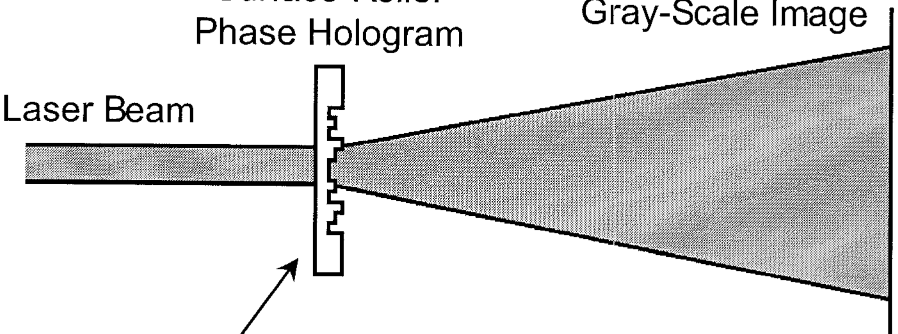


Computer-Generated Holograms

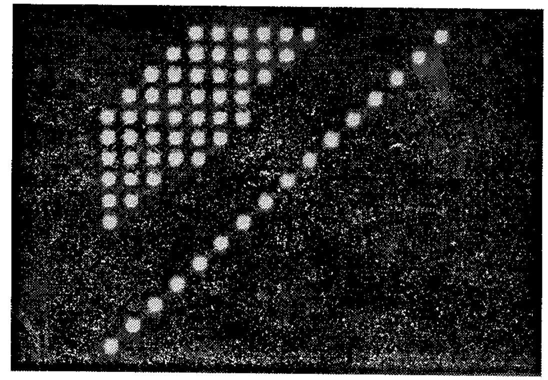
E-Beam Written Surface-Relief Phase Hologram

High-Contrast Gray-Scale Image

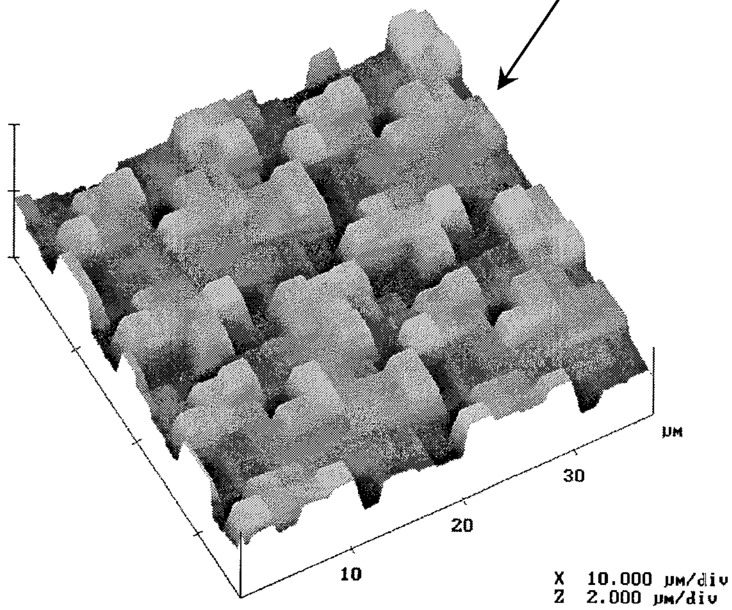
Incident Laser Beam



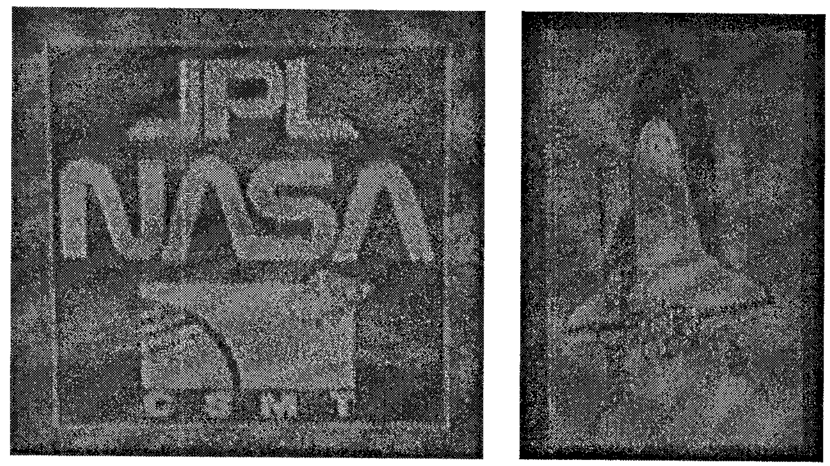
Spot Arrays



Example CGH Surface Profile (AFM Image)



Gray-Scale Images



Imaging Spectrometry

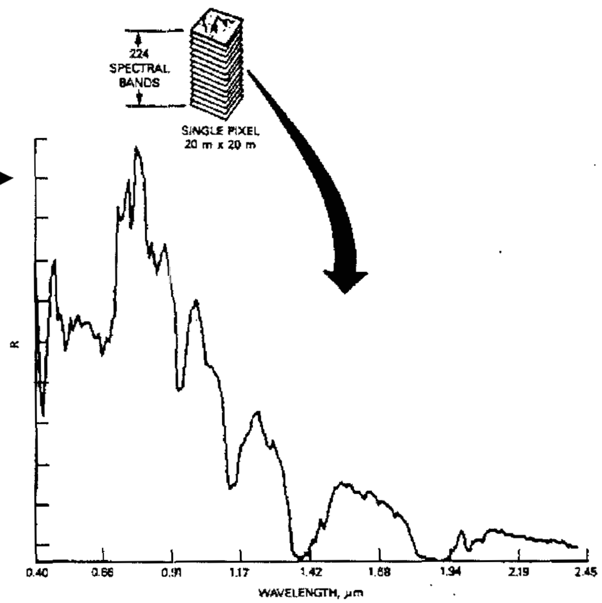
1. Measure the spectra of all pixels in a scene
2. Analyze the spectra to obtain useful information about the scene

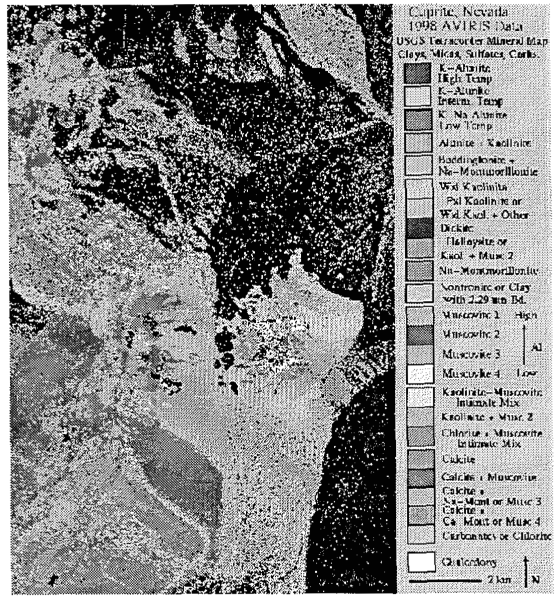
Applications

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





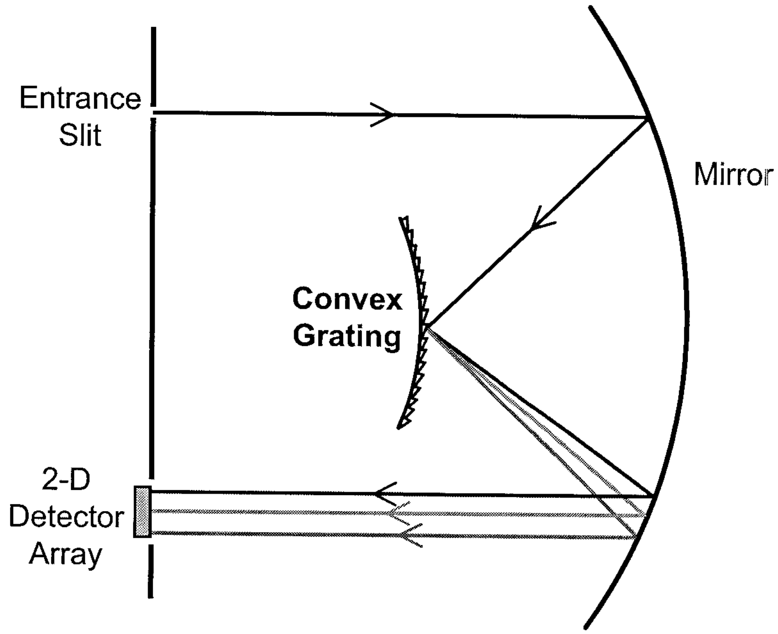
AVIRIS Data of Cuprite, Nevada

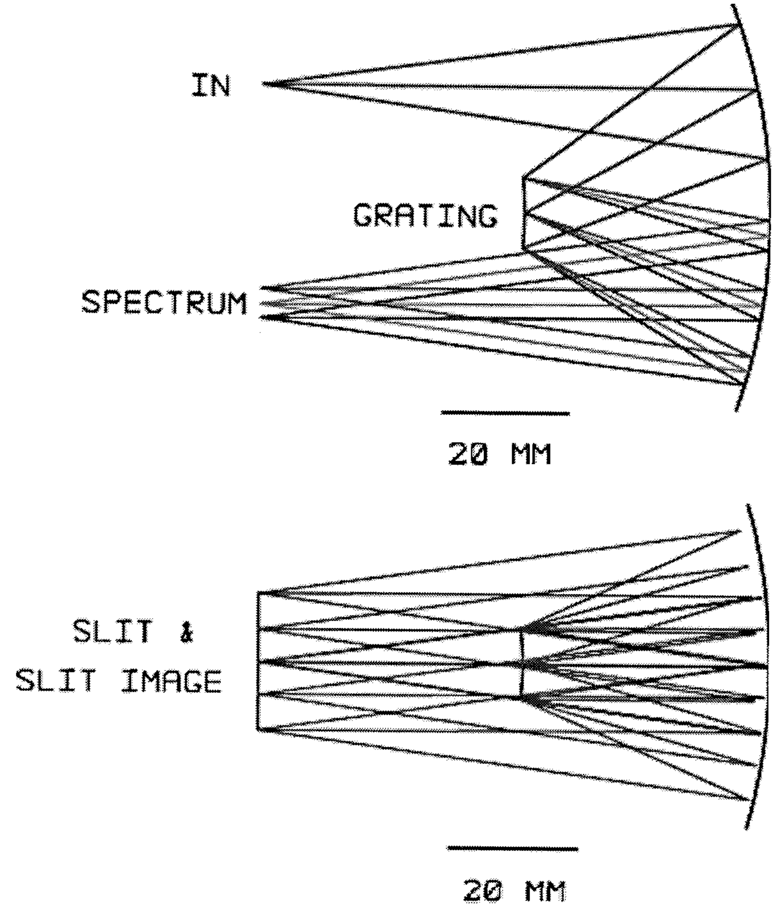
Slit Imaging Spectrometer

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

Offner Imaging Spectrometer Design

Slit imaging spectrometer based on the Offner concentric two-mirror design

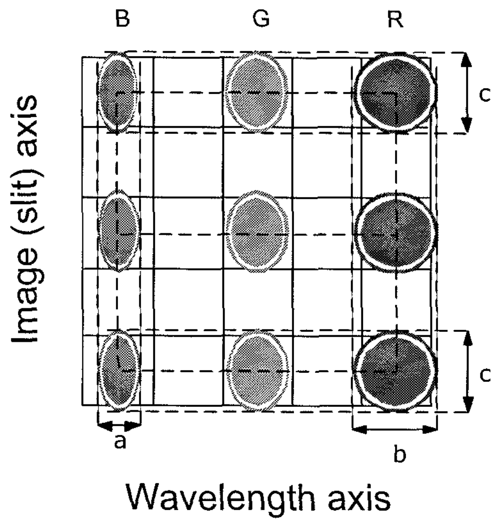




- Can be designed to have *very low slit-image distortion*
  - Minimizes pixel crosstalk
  - Greatly simplifies calibration of the spectrometer
- Can be very compact and lightweight
- Requires a convex grating (blazed for high efficiency)

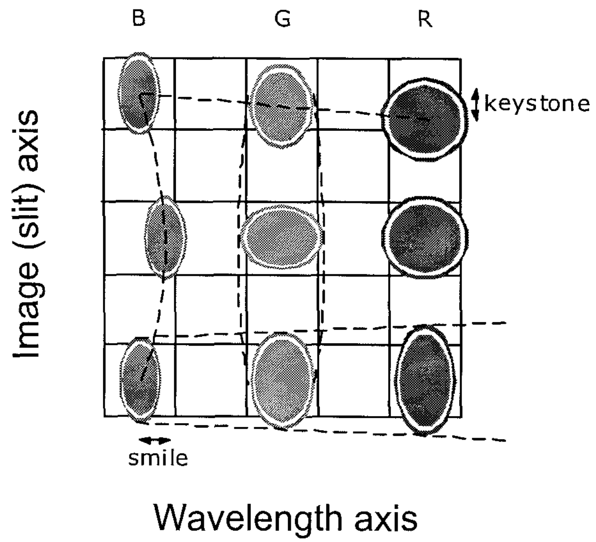
Spectra Distortion in Pushbroom Imaging Spectrometers

Ideal



High spectral and spatial uniformity

Distorted

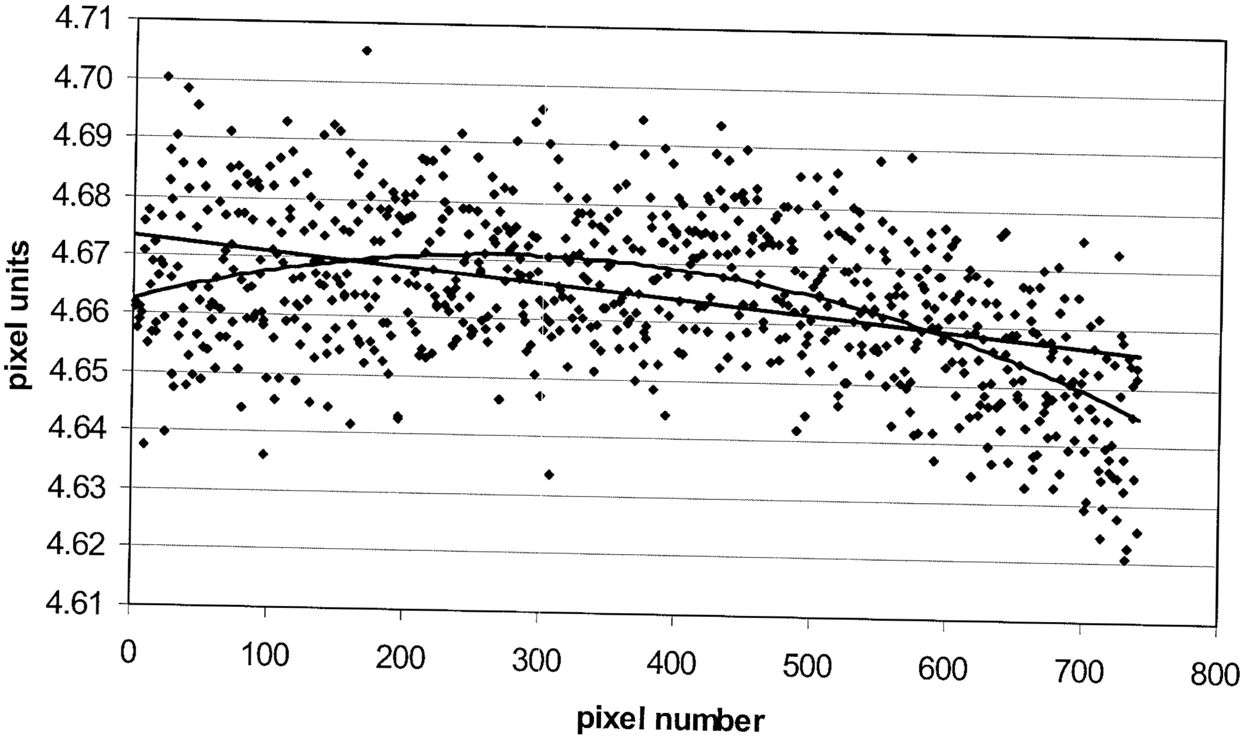


Low spectral and spatial uniformity
Compromises data recovery

Mouroulis et al., Appl. Opt. **39**, 2210 (2000)

Measurement of Offner Spectrometer "Smile"

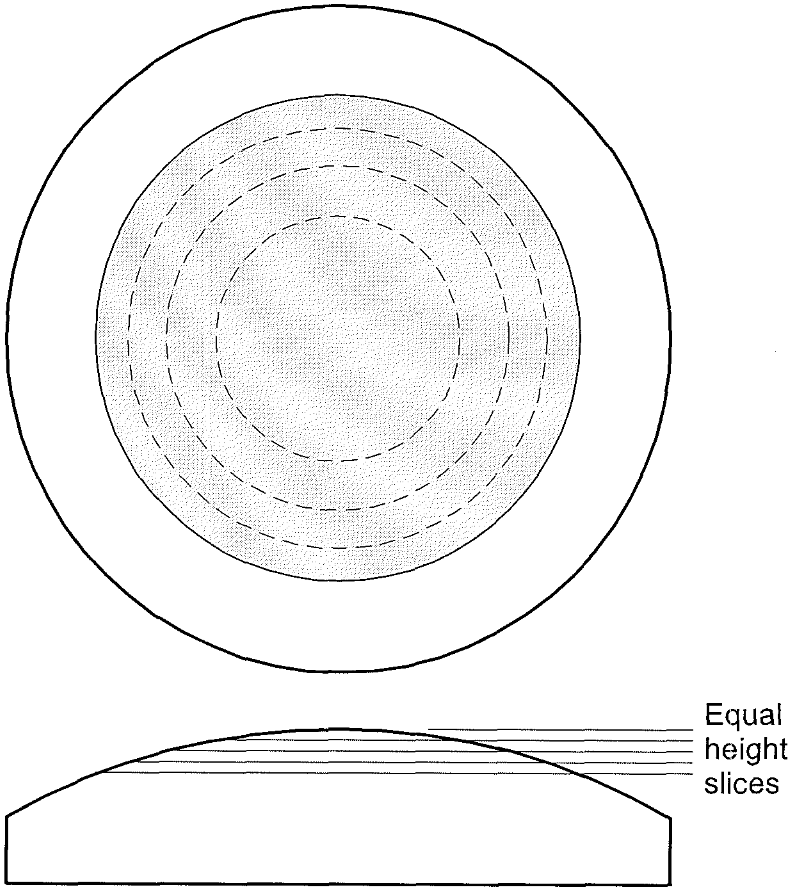
Image of the 546.1 nm Hg spectral line: smile < 0.03 pixel



Mouroulis and McKerns, Opt. Eng. **39**, 808 (2000)

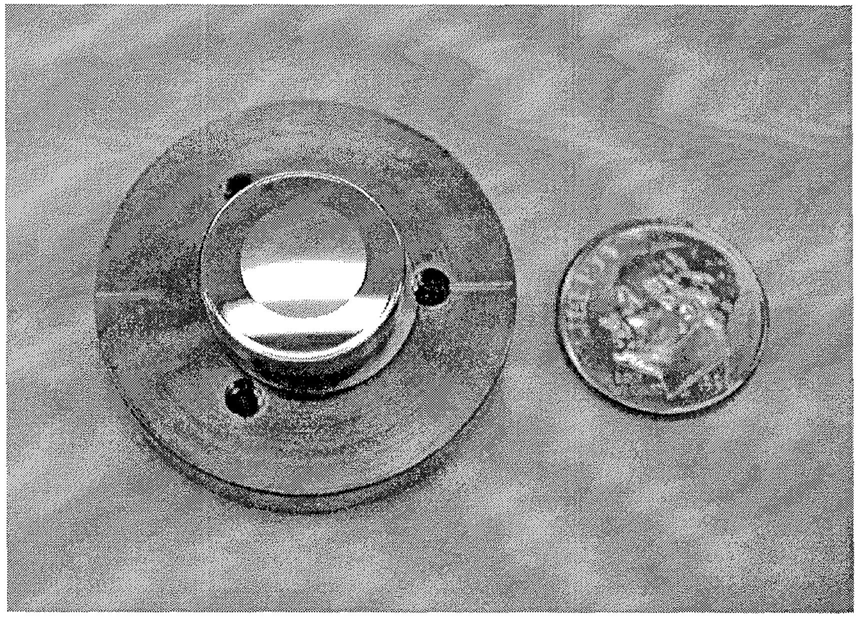
Convex Grating Fabrication

- Pattern is broken in to annular sections that cover equal height steps of ~50 microns (E-beam depth of field)
- E-beam *focus, deflector gain, and rotation* are corrected for each annular pattern



Single-blaze grating on aluminum substrate for *NASA New Millenium EO-1 Mission*

- Selected over diamond-ruled and holographic gratings based on measurements of efficiency, scattering, and wavefront quality



Convex Grating Performance

Delivered gratings for

- TRW Hyperion (NASA New Millenium EO-1 mission)
- Another project "Spectrometer 1 and Spectrometer 2"

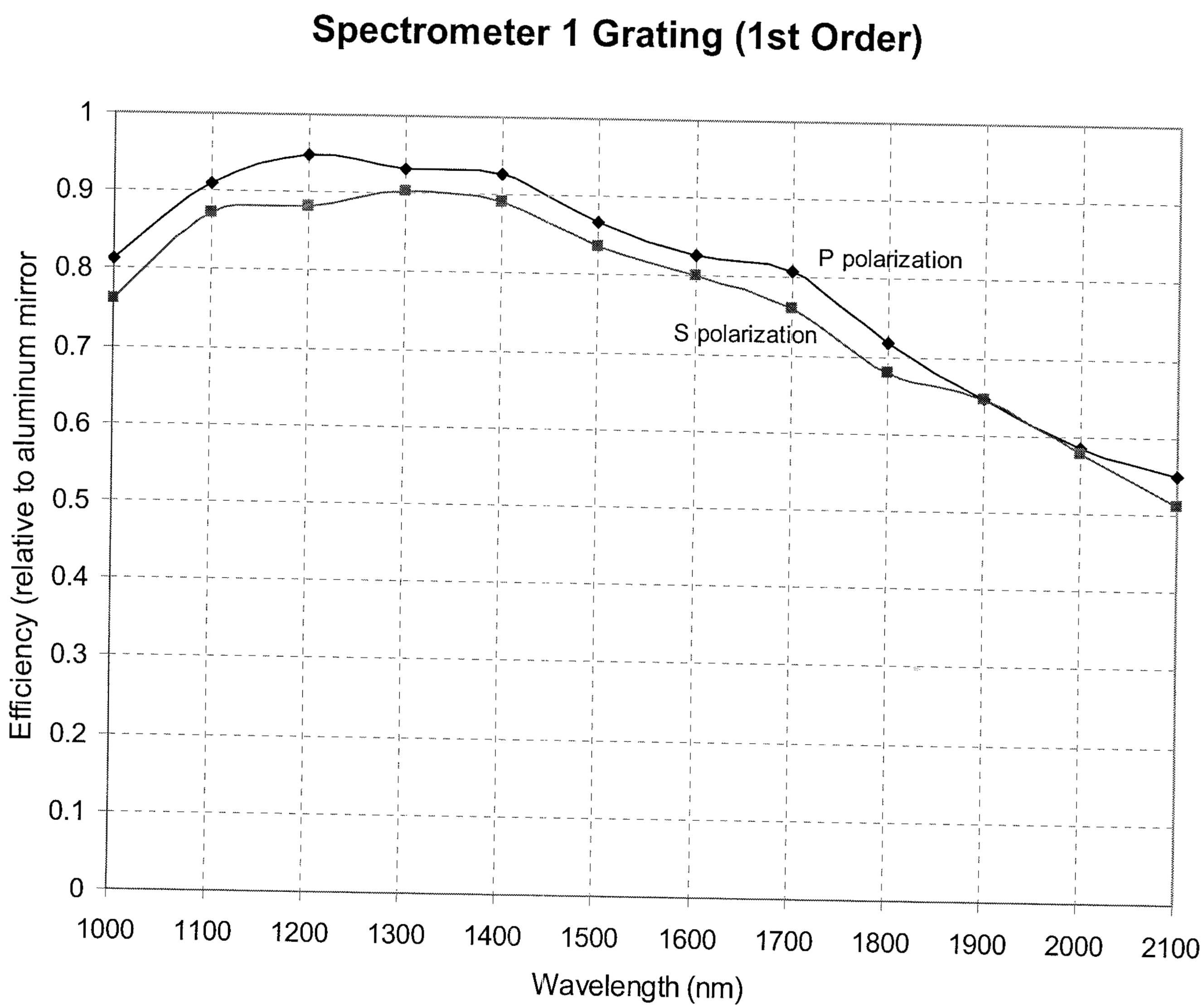
Specifications and performance of flight-instrument gratings

Grating	Diameter	Period	Blaze Angle	Substrate Sag	Wavelength range (order)	Peak Efficiency†, Wavelength (order)	Ghosts, Scatter‡
Hyperion VNIR	14 mm	17.4 μm	0.55 deg	0.23 mm	0.4 – 0.85 μm (-1)	92% @ 490 nm	0.025%
Hyperion SWIR	14 mm	17.4 μm	2.27 deg	0.23 mm	1.13 – 2.55 μm (-1)	92% @ 1450 nm	0.16%
Spect. 1 Dual-band	29 mm	35.7 μm	1.19 deg	1.27 mm	0.5 – 0.85 (-2) 1.0 – 2.45 (-1)	91% @ 0.63 μm (-2) 93% @ 1.26 μm (-1)	0.05%
Spect. 2 MWIR	36.6 mm	103.6 μm	1.12 deg	0	3 – 5 μm (-1)	Not Meas.	Not Meas.

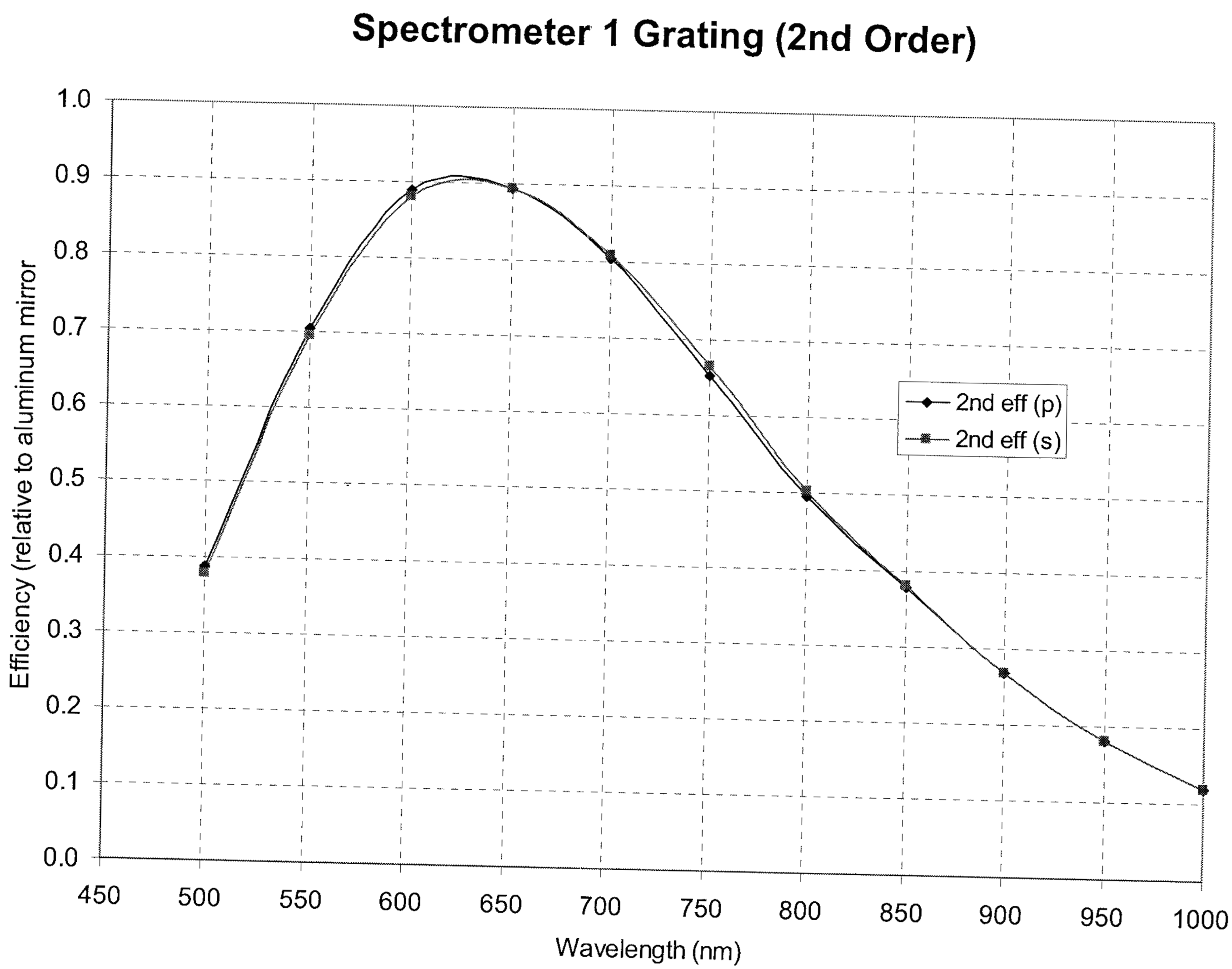
† - relative to an aluminum mirror

‡ - compared to the brightest order at 633 nm, in all cases ghosts dominated over diffuse scatter

Efficiency


Spectrometer 1 Grating (1st Order)
Efficiency (relative to aluminum mirror)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Wavelength (nm)
P polarization
S polarization

Efficiency



Spectrometer 1 Grating (2nd Order)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Efficiency (relative to aluminum mirror
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength (nm)
2nd eff (p)
2nd eff (s)

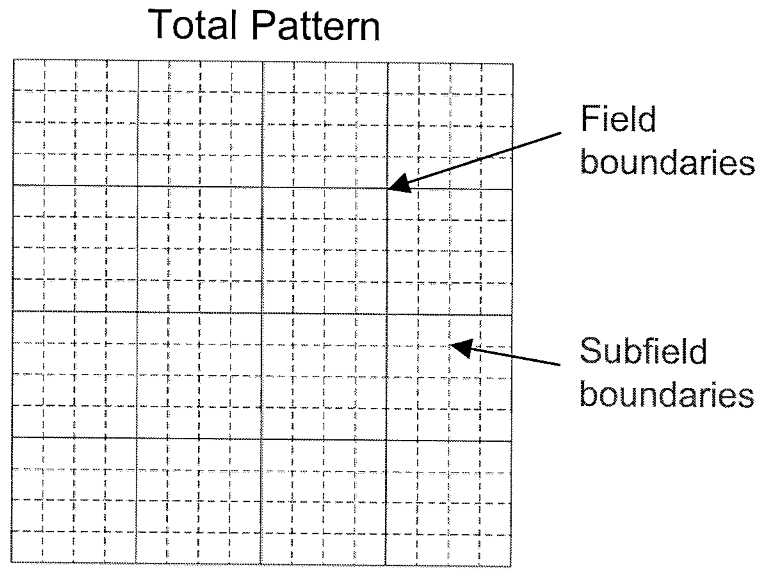
Ghost Diffraction Orders

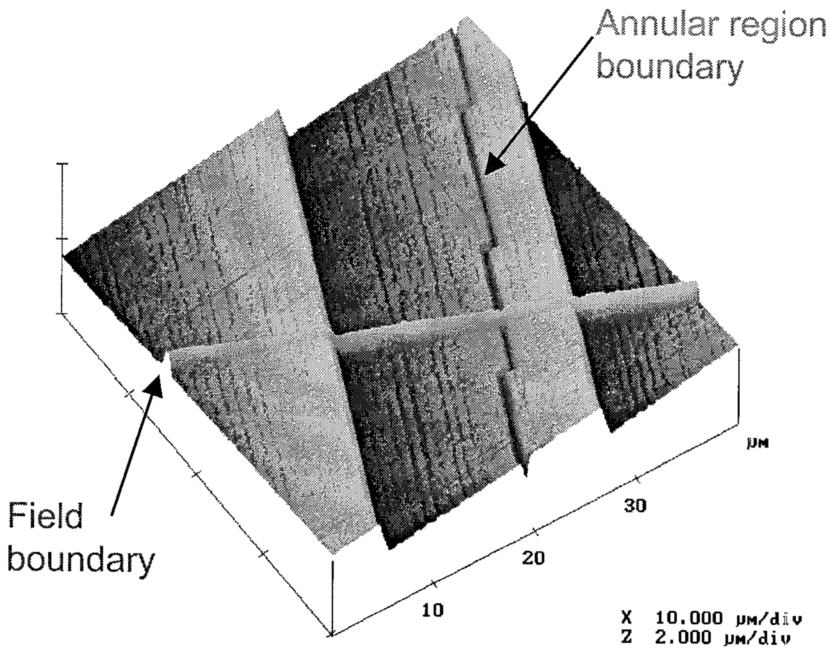
Pattern broken into square regions (JEOL JBX5D2)

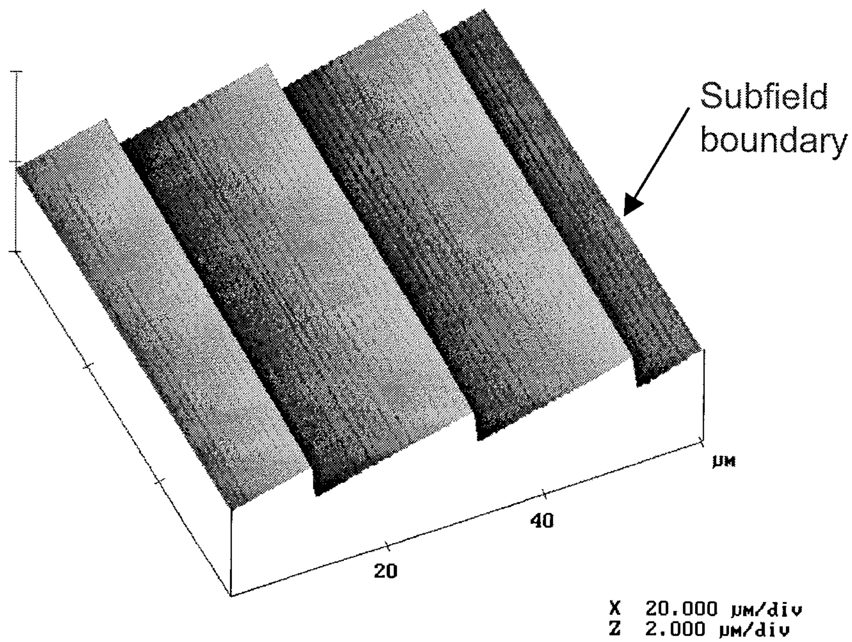
- Fields (800 microns max) - stage moves
- Subfields (100 microns max) - region of deflector calibration

Subfield ghost orders

- If *N* periods per subfield
- Period for ghost is *N* times grating period, so sine of ghost angle is 1/*N* times sine of grating angle
- *N*-1 ghost orders appear between main diffraction orders

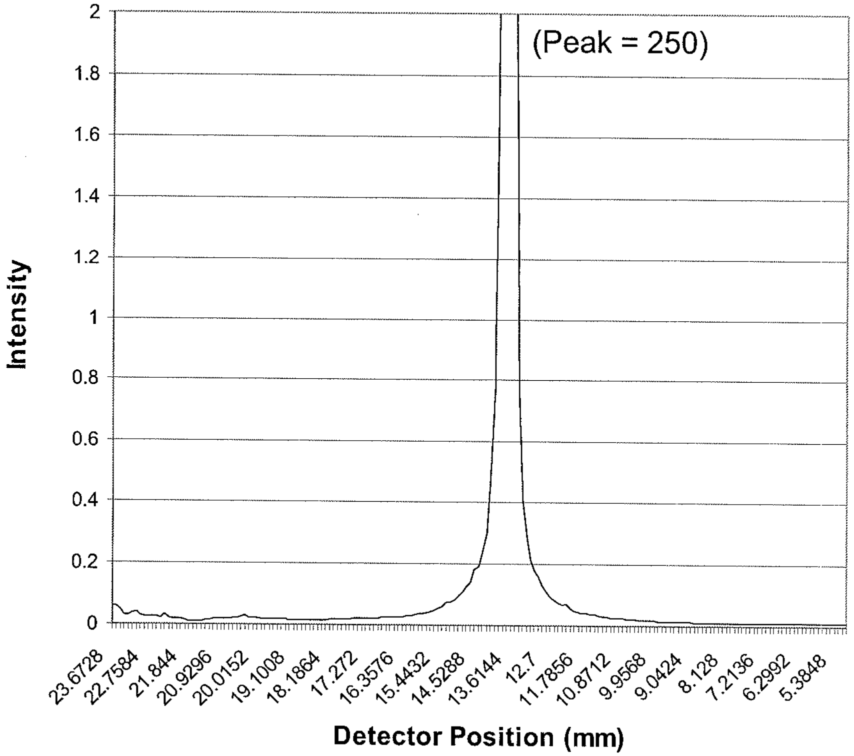






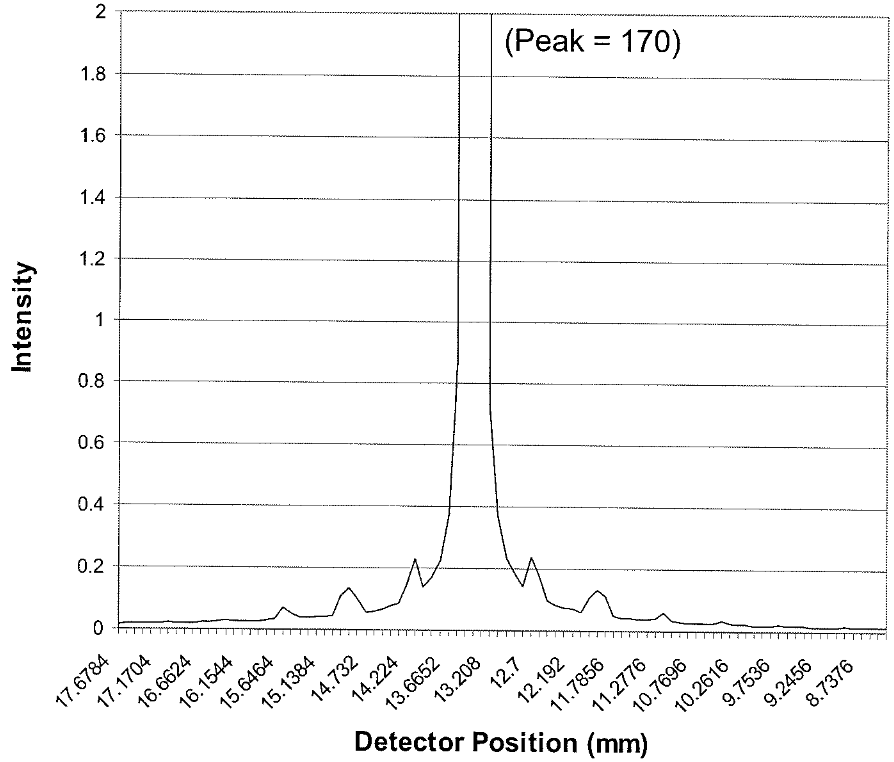
Ghost Diffraction Orders

VERTICAL SCATTER of VNIR GRATING (S/N 7)



Scatter = 0.025%

VERTICAL SCATTER of SWIR GRATING (S/N 3)

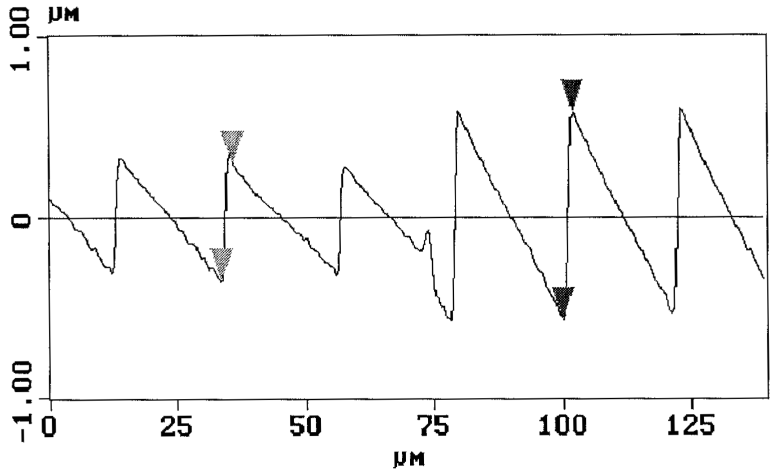


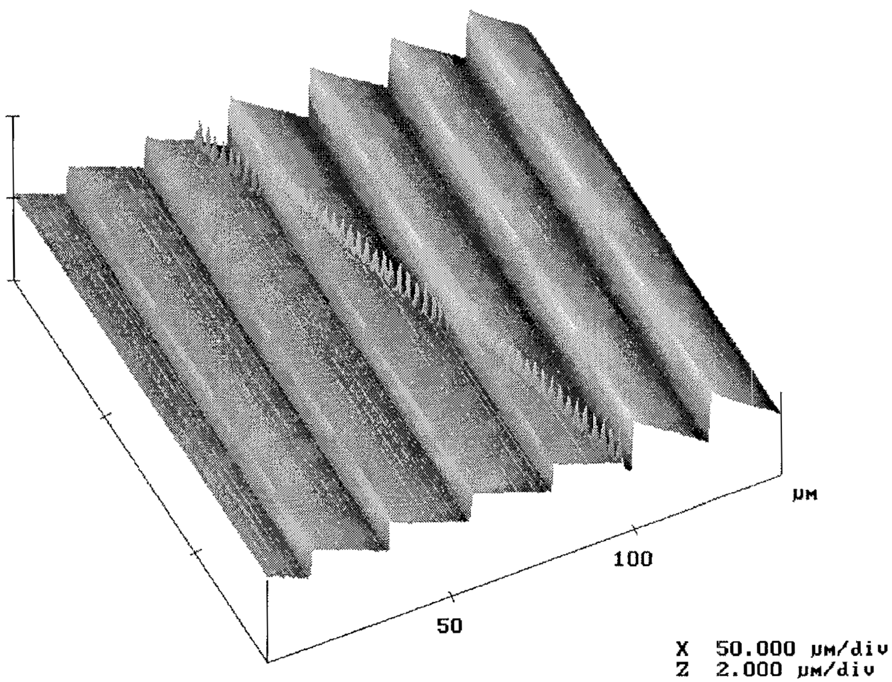
Scatter = 0.16%

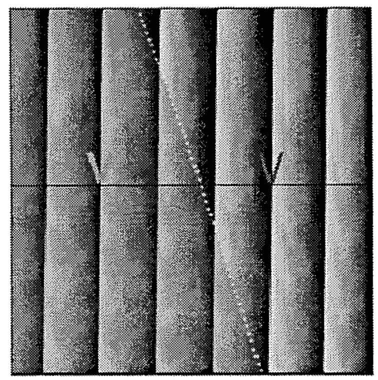
Dual-Blaze Convex Grating

- Constant period over entire area
- Two blaze angles:
  - center circle blazed for visible
  - outer annulus blazed for infrared
- <u>High Efficiency for both Visible and Infrared</u>
- Provides flat and high signal to noise ratio.

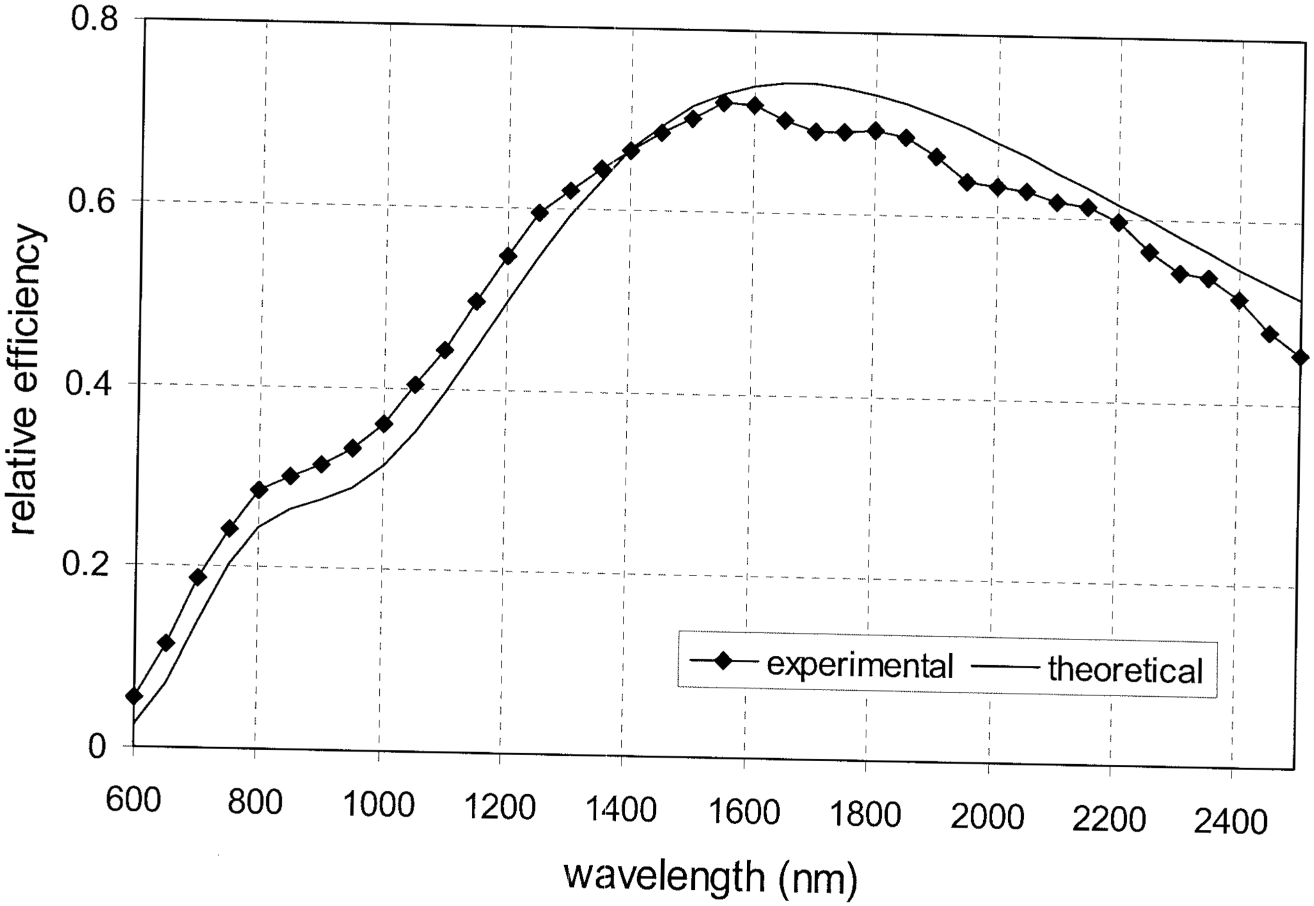
AFM profile of a dual-blaze convex grating showing blaze-angle zone boundary





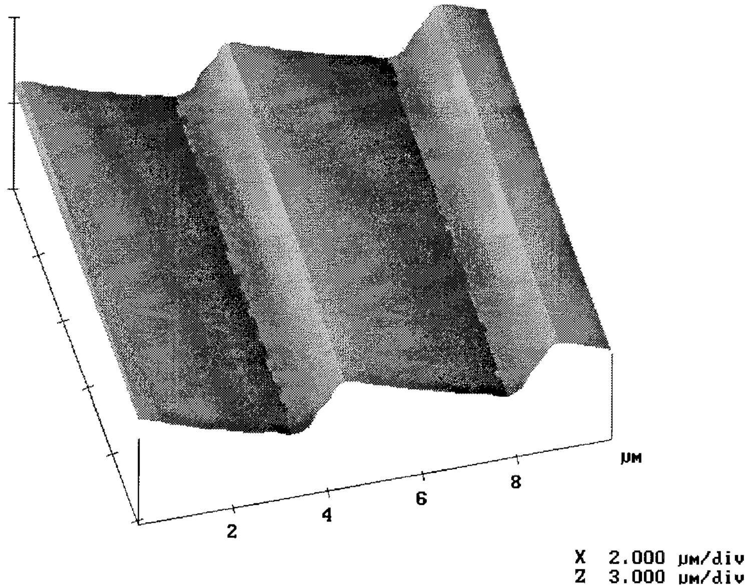


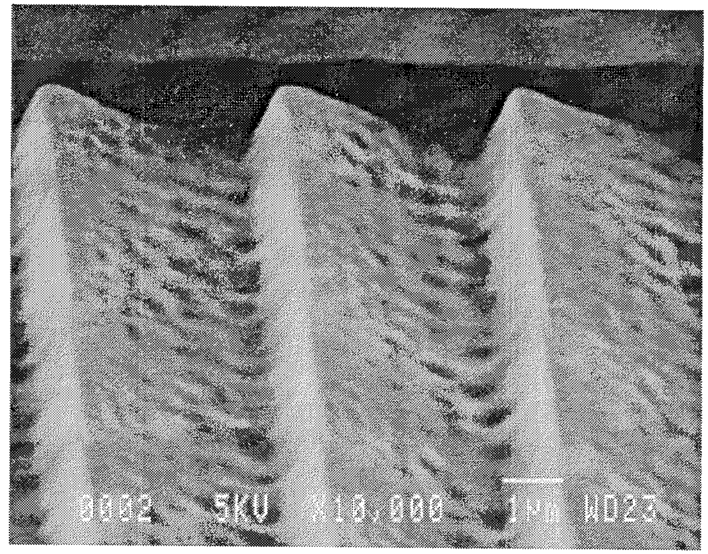
Dual-Blaze Grating Efficiency

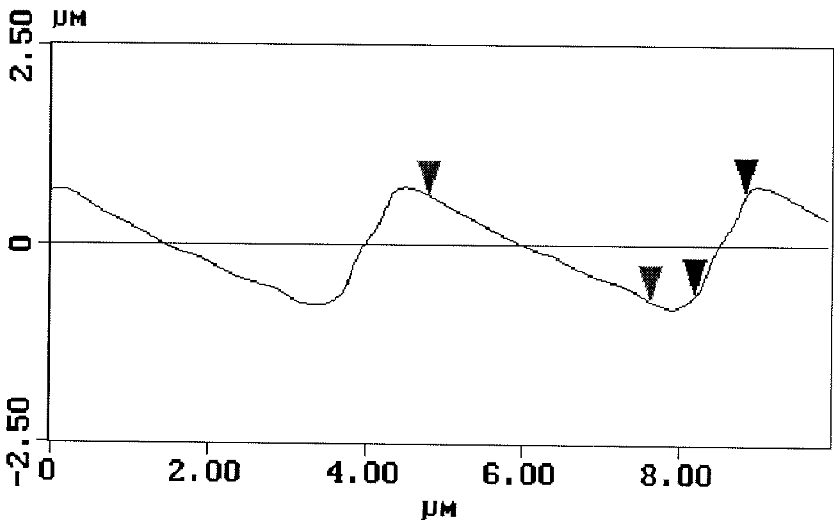


Echelle Gratings

- Period = 4.34 microns
- Blaze angles = 26.2 deg, 63.8 deg (depth = 1.626 microns)



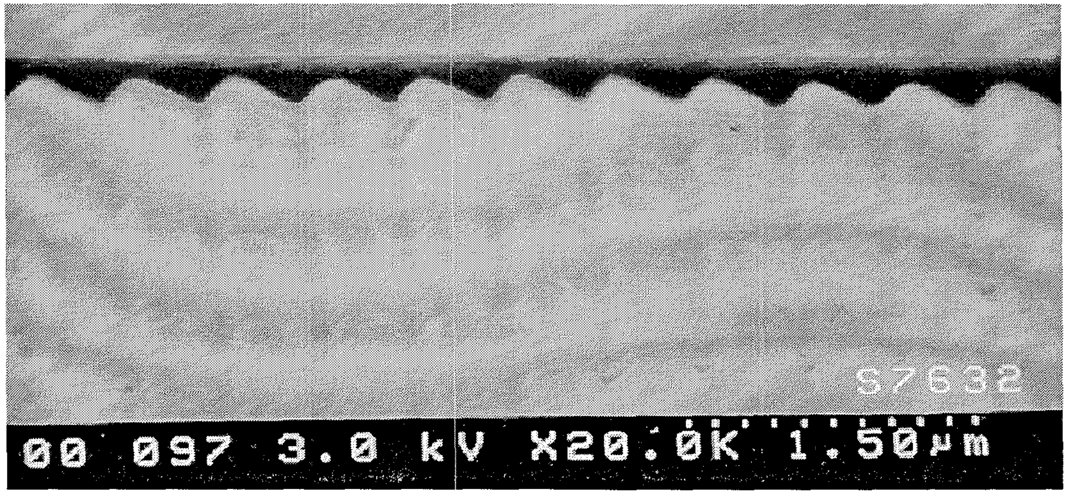




Horiz distance(L)	2.813 µm
Vert distance	1.316 µm
Angle	25.068 deg
Horiz distance	625.00 nm
Vert distance	1.269 µm
Angle	63.776 deg

Sharp AFM tip was used so both angles are accurate.

Blazed grating with 0.5 micron period (2000 lines/mm)



Summary

- Analog E-beam lithography can produce high-performance diffractive optical elements
- Convex gratings are required for Offner imaging spectrometers
- Direct-write electron-beam fabrication technique works well
  - Non-flat substrates (convex or concave, aspheric)
  - Very efficient blazing (arbitrary groove profile)
  - Can write non-straight grooves for aberration correction
  - Ghost orders and roughness can be improved
  - For fine-period gratings, field stitching is an issue

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Abstract

Electron-beam lithography can be used to fabricate high-performance analog-depth diffractive optical elements (DOEs). We have recently extended our technique to allow fabrication of analog DOEs on non-flat (convex and concave) substrates. Specifically, we have fabricated convex blazed gratings that exhibit greater than 90% diffraction efficiency. Several of our gratings have been used in compact space borne imaging spectrometers. We will describe the details of our fabrication process including height calibration, pattern fracturing, proximity effect compensation, E-beam exposure, and resist development.