Silicon Diffractive Elements by projection photolithography.”

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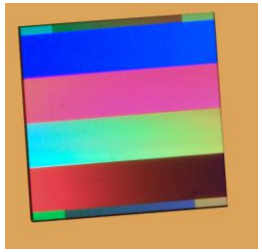
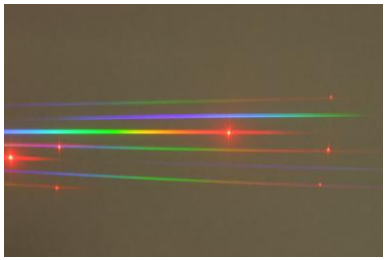
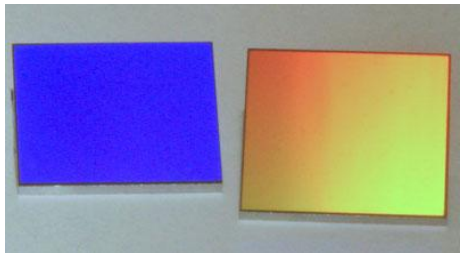
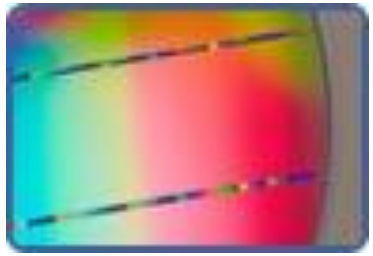
Crafting Light For The Information Age
LightSmyth Technologies

LightSmyth Technologies

- Founded in 2000
- Mandate to use advanced optical design algorithms and state-of-the-art CMOS tools for optics and photonics
- Currently offers 5 product lines with more than 30 products with applications in optical components, photonics, chemistry, biology, physics and even decorative items.

Outline

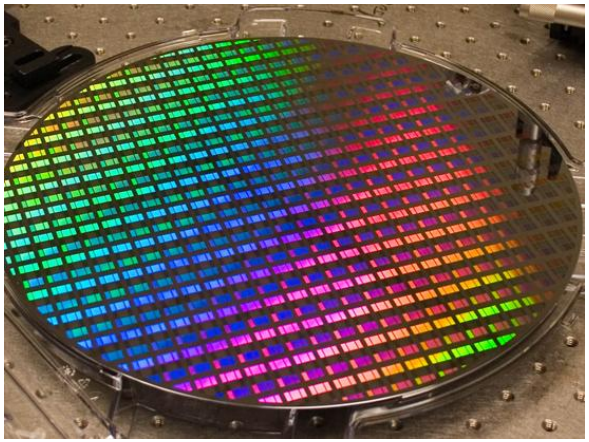
1. Background. Principles and advantaged of DUV photolithography for diffraction structures fabrication.
2. Creation of new technological platform

- NEXUS grating prototype: design and fabrication approach - spherical substrate.
- Constellation-X grating prototype: design and fabrication approach - flat substrate.

3. Conclusion

Nanostructured grating advantages

Arbitrary groove patterns- First significant innovation in grating fabrication in the last 40 years since introduction of holographic gratings



- Advanced aberration control
- Aspheric focusing on flat substrate
- Grating arrays
- Ultrahigh density gratings (7200 lines/mm)
- Low stray light (10 to 100 x better than holographic gratings)
- Single crystal silicon substrate TEC better than that of PIREX
- Thermal conductivity close to that of aluminum
- Robust and cleanable, thin and lightweight

Mask fabrication: Laser Writer

Micronic Laser Systems AB

- Write time (6” mask) 1 h 45 min
- Minimum main feature 220 nm
- Address grid 1.25 nm
- CD uniformity (global, 3 σ) 7 nm
- Registration (global, 3 σ) 15 nm

Resist Patterning: DUV Reducing Scanner

- Reduction Factor 4x (from mask)
- Resolution 65 nm
- Field Size 26 X 33 mm
- Throughput 122 wph

  300 mm wafers

  125 exposures

- Exposure wavelength:

248 nm, 193 nm, 193 nm immersion

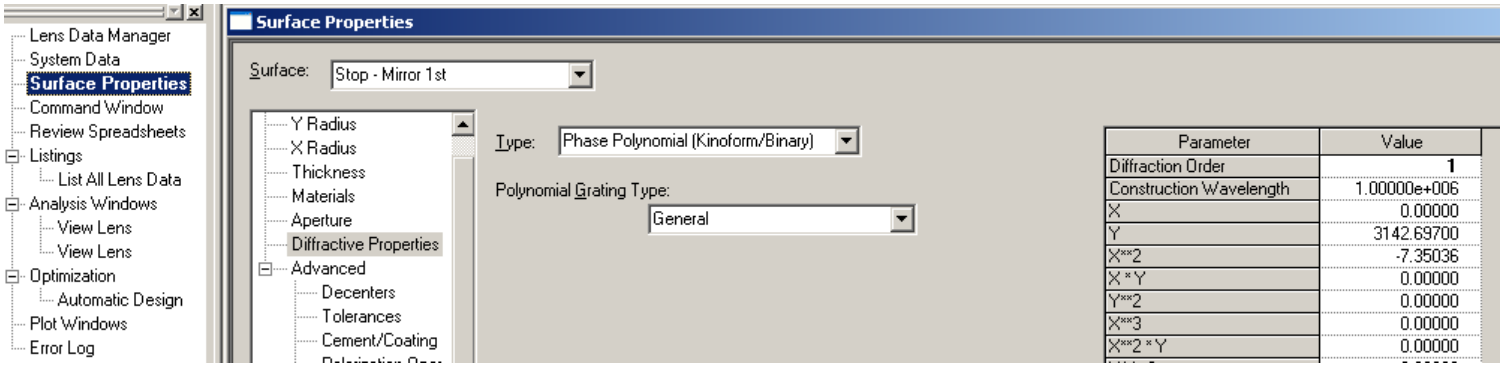
Creation of new technological platform

1. Simulation capabilities
- Custom software
- Commercial software (ZEMAX, Code V)

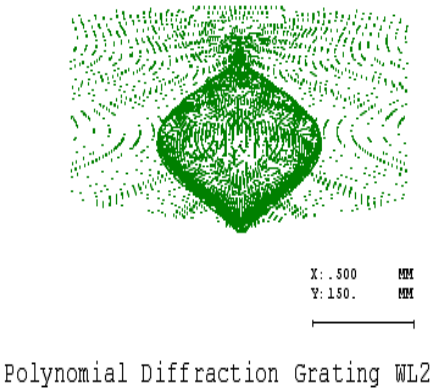
2. Understand properties of variable line spacing and curvilinear groove gratings.
- Focusing on flat substrate
- Improved aberration control

3. Precise control of groove morphology (shape, duty cycle, multiple layers)
- New types of blazing – improved diffraction efficiency

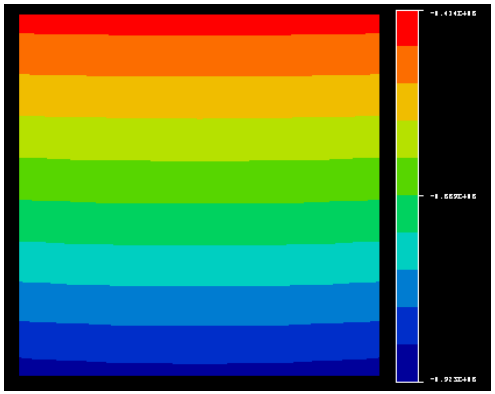
Developed Simulation tools based of Code V



Window defining properties of Phase Polynomial Diffraction surface.



Spot diagram for diffractive contours on flat substrate



Phase distribution of diffractive contours on flat substrate

Ability to simulate curvilinear gratings with variable period is critical in their adoption.

Use build-in feature of Code V: analytical phase function in surface diffractive properties.

Phase polynomial: standard feature.
Custom modules: anything that may be expressed analytically is easy to integrate into Code V through .dll module.

2. Focusing on flat substrate: when is it useful

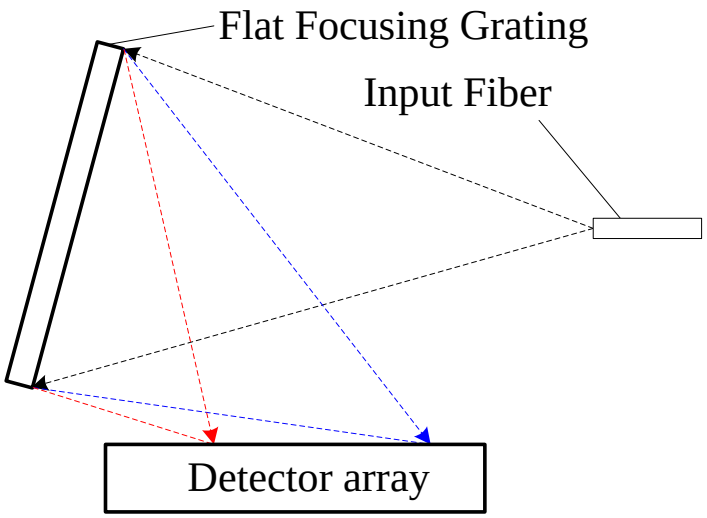
Flat-substrate focusing gratings advantages:

- Are easier to fabricate and coat than concave substrate gratings.
- Better aberration control and higher efficiency
- May be used for very fast optics (F# close to 1), as holographically designed focusing is "perfect" for design wavelength even at non-paraxial angles (aspheric optics capability on flat substrate)

Focal length is wavelength dependent.

Useful to "flatten" focal plane when:

- small relative wavelength range $\delta\lambda/\lambda$ or
- comparable focal length and detector size



Example: micro-spectrometer

When groove-based focusing is not enough..

…Groove curvature and variable spacing still may be very useful for aberration control – use cheaper simpler optics:

NEXUS grating (originally VLS on thoroidal substrate) for EUV

Constellation-X (off-axis grating) X-ray grazing incidence

Grating for NEXUS

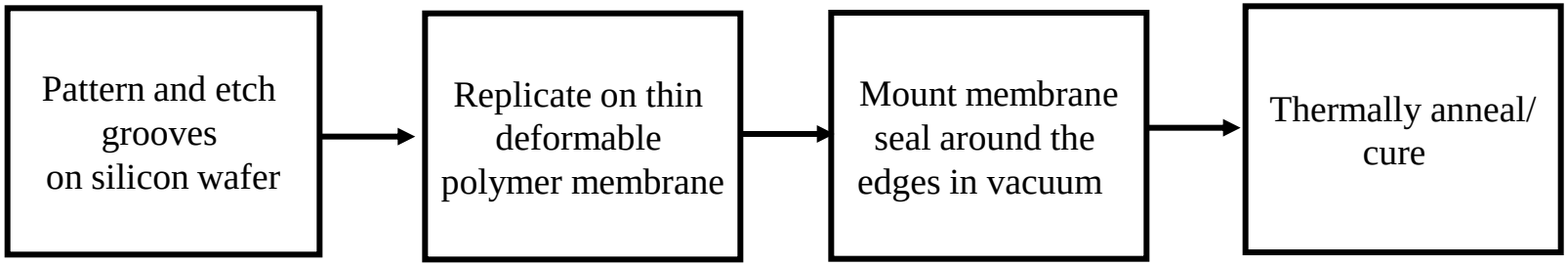
(Normal incidence EUV spectrometer to study outer atmosphere of Sun)

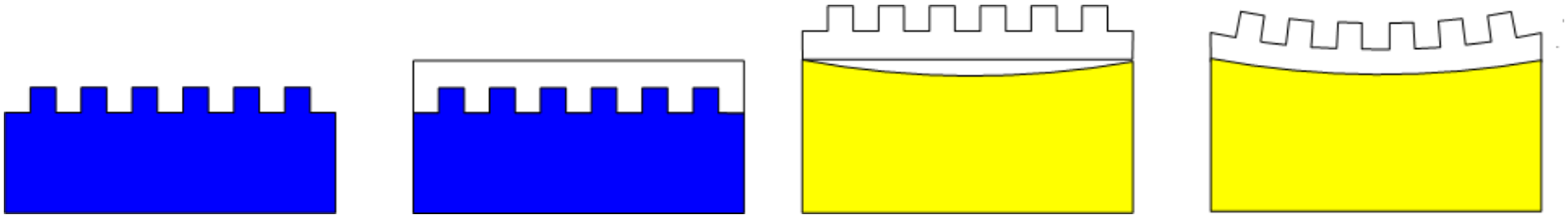
Objective: provide product meeting NASA specification of NEXUS grating

Challenging design task: wavelength range 45.7-120 nm. Due to wide relative wavelength range and ratio of focal length/detector, flat substrate focusing will not work.

Pathway: curved groove variable line spacing on spherical substrate.

Grating for NEXUS (cont): fabrication pathway





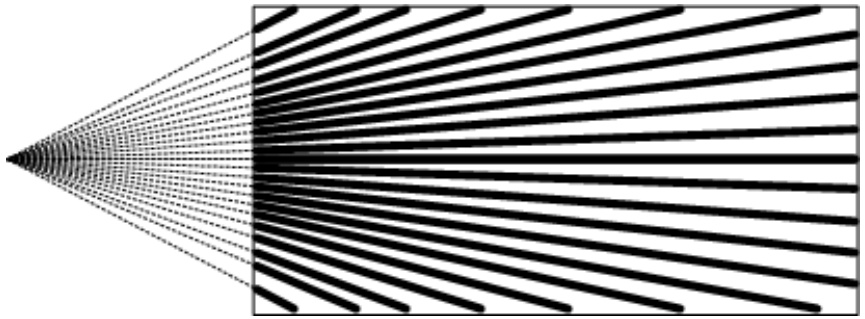
Aberration control beyond type IV holographic gratings.

Same or better performance on spherical substrate as regular VLS holographic grating on thoroidal substrate

Constellation-X Off-axis Grating Prototype

Objective: Demonstrate feasibility of technology for X-ray spectrometer

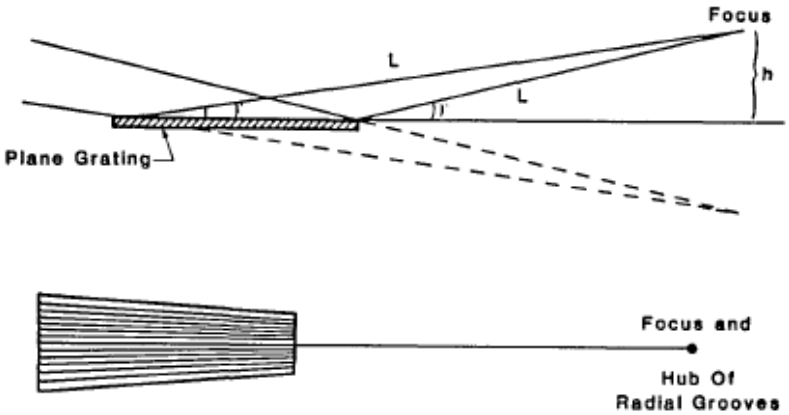
- Design and testing by group of Professor Webster Cash, University of Colorado
- Mask design and fabrication: LightSmyth

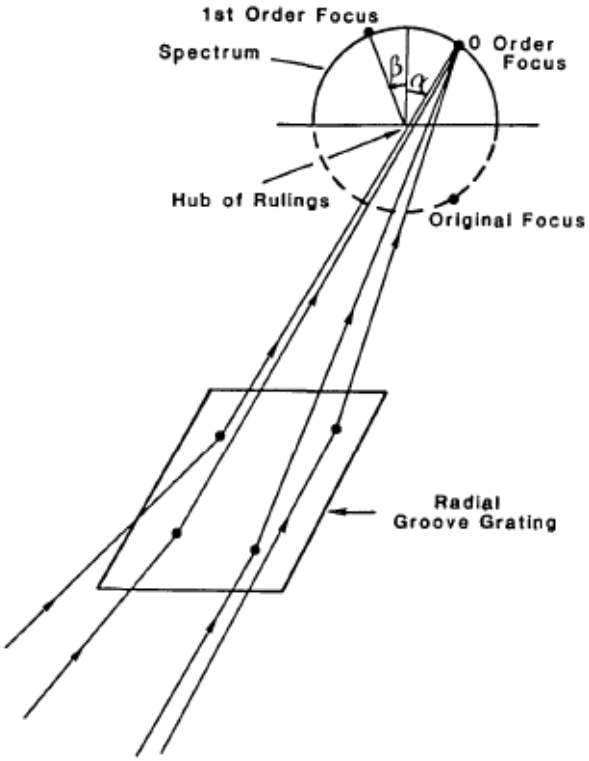


This type of gratings was proposed in 1980th by Dr. W. Cash but no fabrication means were available at that time.

- Offers better resolution per unit area and better aberration control than conventional in-plane grating –> flight weight reduction
- Cannot be easily fabricated by interferometric or mechanical ruling, but trivial in mask-based fabrication

Constellation-X Off-axis Grating Prototype





Conditions for minimum aberrations: grazing angle (used in X-ray)
Light is converging on the grating with projection of the focal point on the grating plane coinciding with the hub (where all the grooves cross).

Webster C. Cash, Jr. "X-ray spectrograph using radial groove gratings", Applied Optics, Vol. 22, Issue 24, pp. 3971-3976

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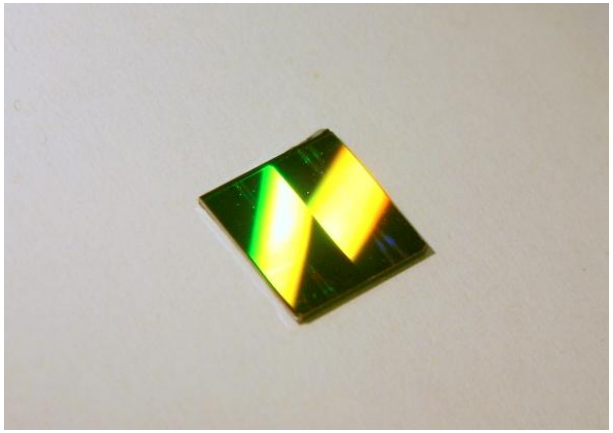
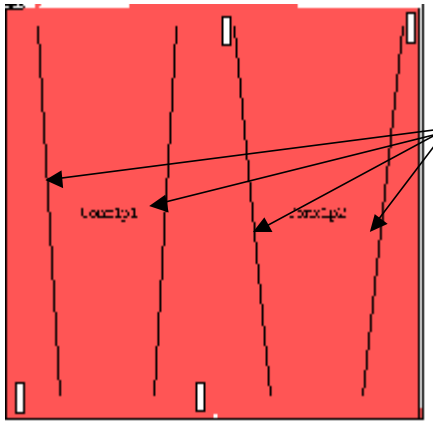
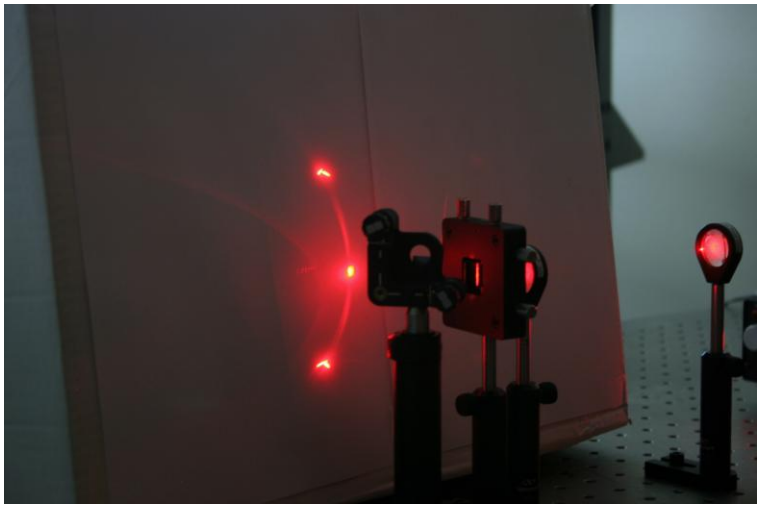


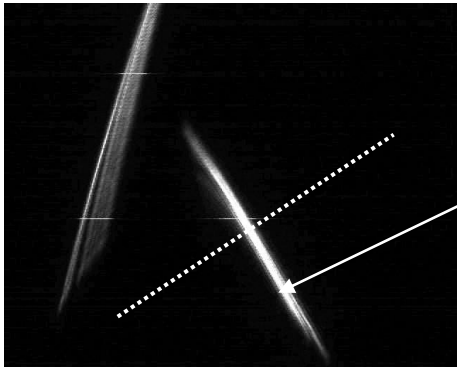


Three gratings fabricated: with hub 100 mm and 200 mm and parallel grooves.

Gratings are tested in converging beams with focal distance 200 mm.

200 mm hub grating output has the highest resolution



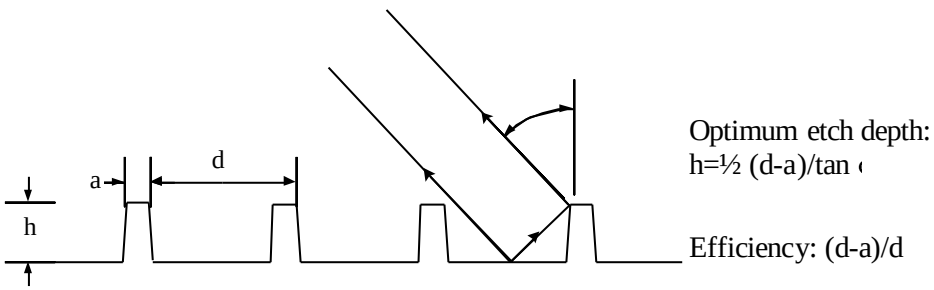


Focused spot from 200 mm hub grating

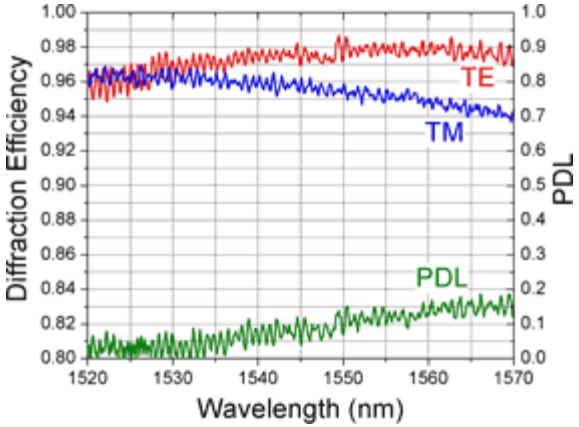
New types of blazing

Rectangular profile gratings can be blazed!

1. Optimizing groove depth and ratio of line to space (suppressing 0th order reflection)- works similar to triangular profile blaze.
2. Using roof-top blazing – works for wide range of angles
3. Using dielectric stack.



roof-top blazing



Dielectric stack grating

Conclusion

New approach to diffraction grating design and fabrication allows for powerful new classes of diffraction optical elements

- Developed basis of technological platform:

=>Complete simulation capability with commercial software

=>Strengths and limitations are well understood

- Useful in multiple NASA programs
  - Constellation-X
  - Nexus
  - Others

Thank You!

Special thanks to NASA SBIR program and our technical monitor David Content technical input and continuous support.