Structured-Groove Phase Gratings for Control and Optimization of Spectral Efficiency

Johan P. Backlund*, Daniel W. Wilson, and Richard E. Muller

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Current address: Alfa Exx AB, Göteborg, Sweden

Outline

I. Motivation

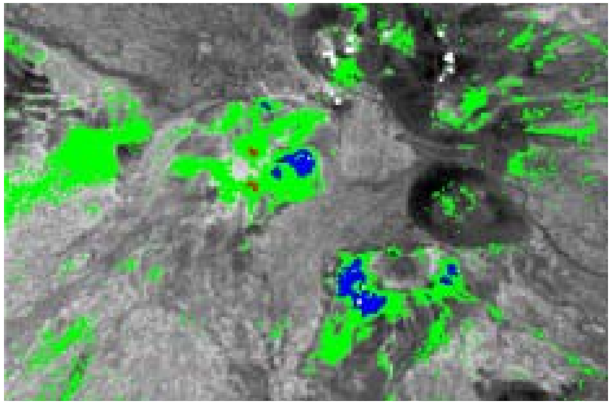
II. Design algorithm

III. Results from fabricated gratings

IV. Current and future work

Motivation

- Imaging spectrometers can perform mapping and classification of remote and in-situ scenes by accurate measurement of spectra.



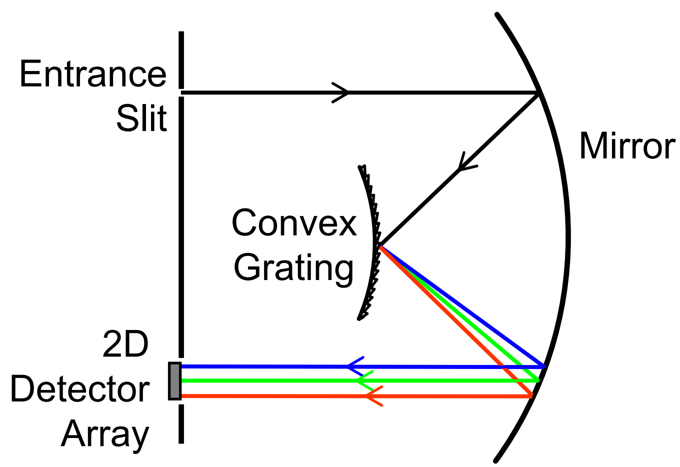
Imaging spectrometer map of Yellowstone that shows the abundance of two different minerals, indicated by green and blue.

Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) aboard the Mars Reconnaissance Orbiter (MRO) will launch in Aug. 2005 to search for traces of past water on the Martian surface.

- Applications of imaging spectrometry include planetary exploration, defense, and bio-medicine.

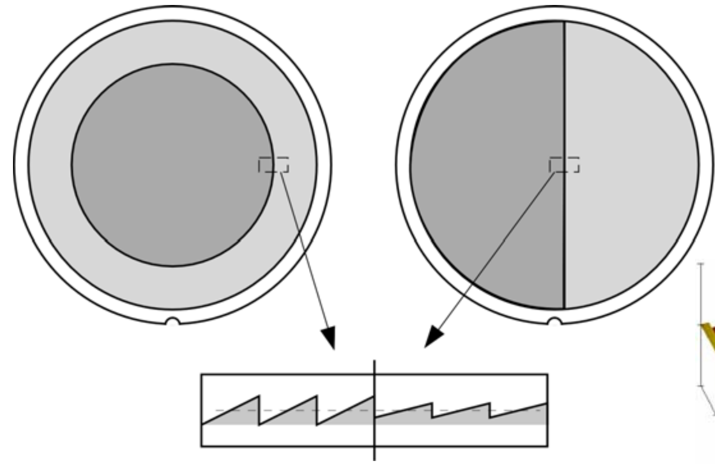
Motivation

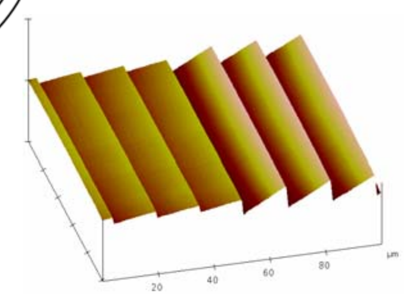
- To achieve broadband operation, state-of-the-art imaging spectrometers use ***multi-blaze*** gratings
  - → Grating split into two or more areas having different sawtooth blaze angles
  - → **Causes undesirable wavelength-dependent apodization effects**

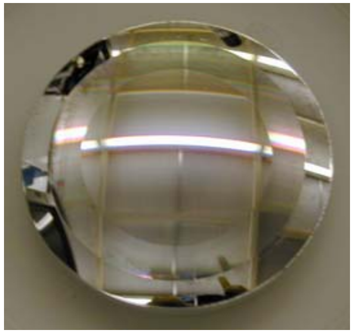


"Offner" slit imaging spectrometer utilizing an E-beam fabricated convex grating

- See Paper FWT2 (Mouroulis et al.) for more examples



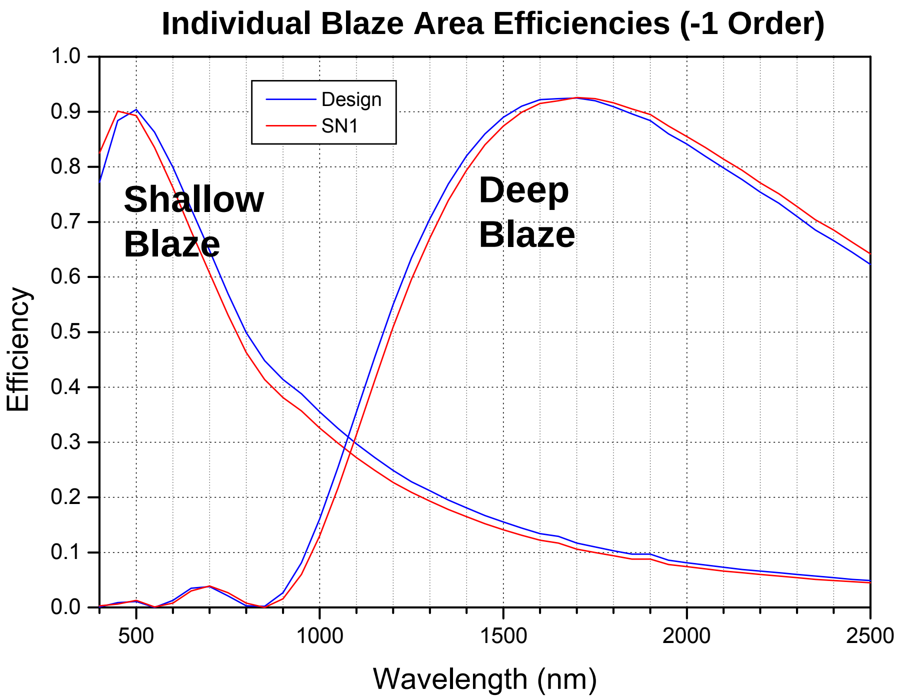


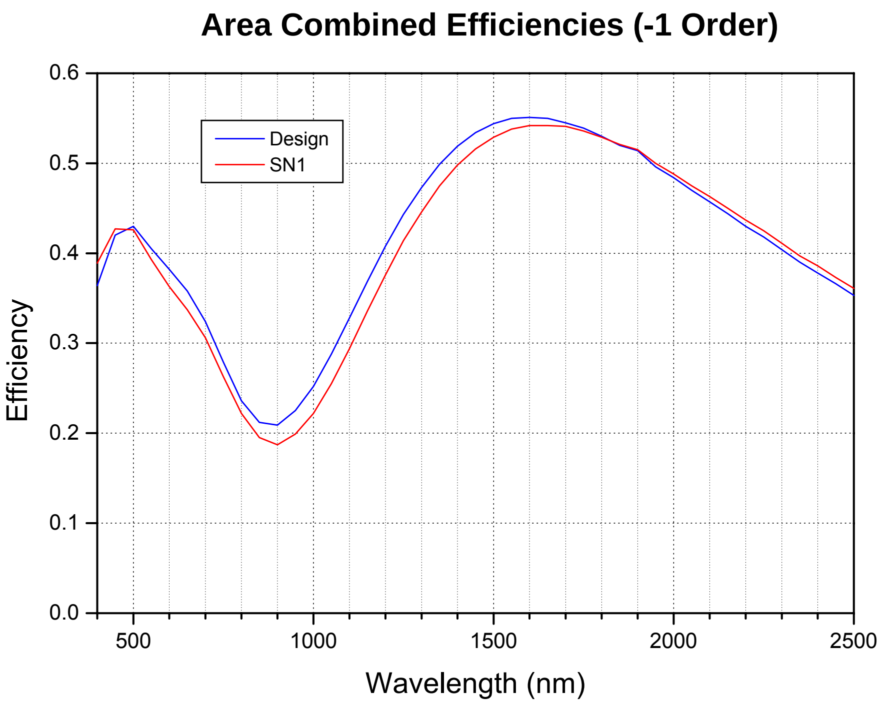


MRO CRISM VNIR grating (400-1100 nm)

Motivation

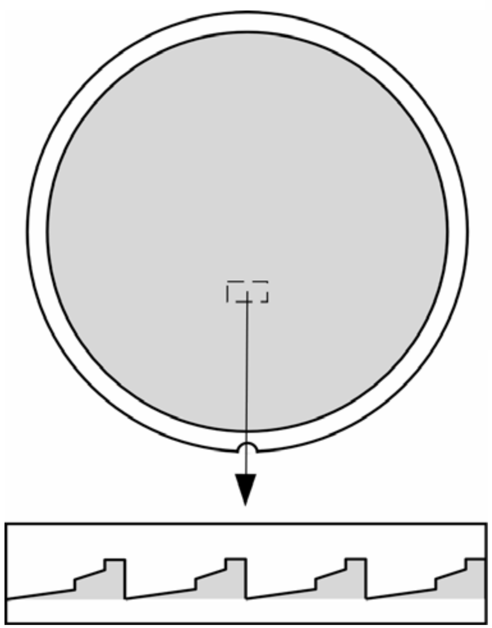
Example Dual-Blaze Grating Efficiency (400 - 2500 nm)

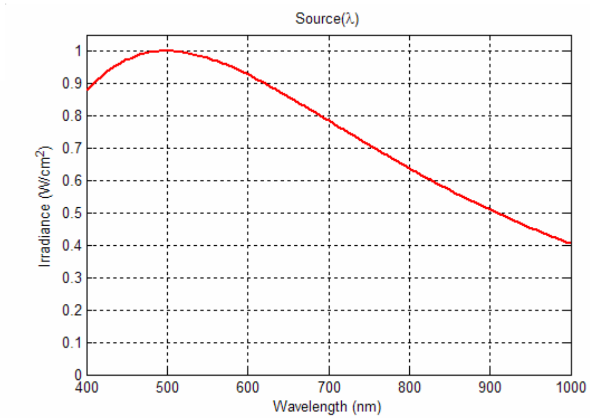


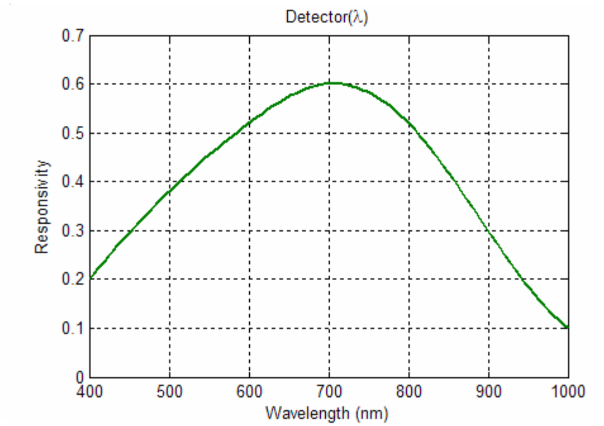


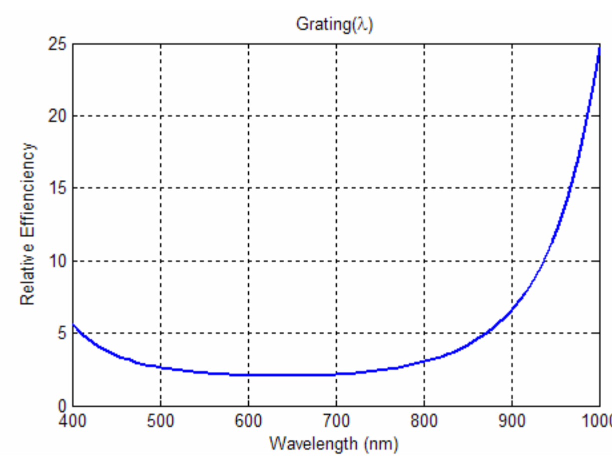
Motivation

- Alternative: **Structured groove grating (SGG)**
  - → single-area grating with an optimized groove shape to achieve the desired efficiency vs. wavelength function
  - → Allows optimization of total instrument = source(λ) × grating(λ) × detector(λ)





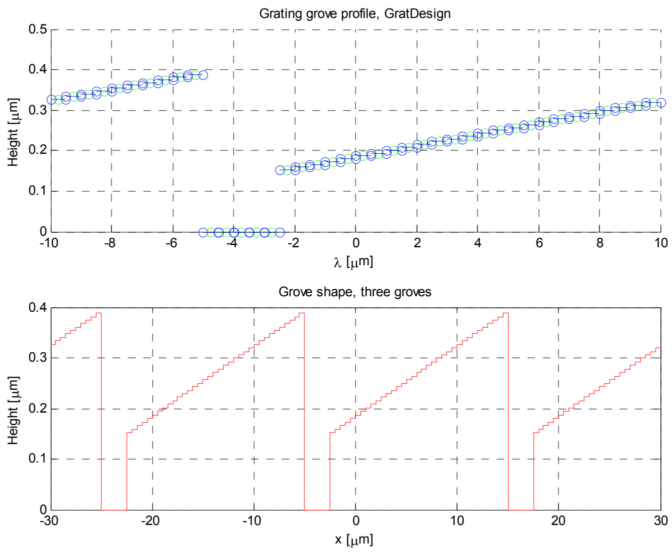


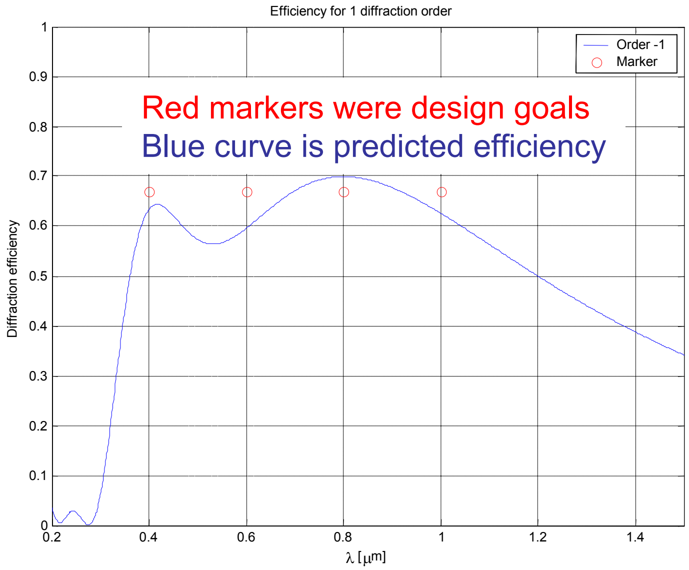


Grating efficiency for unity S/N(λ)

Structured-Groove Grating Design

- Represent groove as piecewise flat pixels and specify set of efficiency targets at different wavelengths for the desired diffraction orders





- Developed spectral version of "optimal rotation angle" (ORA) algorithm to iteratively optimize groove shape
  - → ORA originally developed for designing fan-out kinoforms

    J. Bengtsson, "Design of fan-out kinoforms in the entire scalar diffraction regime with an optimal-rotation-angle method", Appl. Opt., Vol. 36, No. 32, 8453-8444 (1997).
    J. Bengtsson, "Kinoforms designed to produce different fan-out patterns for two wavelengths", Appl. Opt. Vol. 37, No. 11, 2011-2020 (1998).

SGG Design Algorithm (cont.)

Spectral domain Optimal Rotation Angle (ORA) algorithm

1. Specify relative efficiency targets at specific wavelengths and diffraction orders
2. Start with groove composed of random pixel depths
3. For each pixel, find the optimum depth that maximizes its field contribution to all targets simultaneously (maximize the sum)
   - → Targets have relative weights, so this preferentially increases diffraction into strong targets
   - → Maximizes total diffraction efficiency
4. Calculate diffraction efficiencies for all targets
5. Adjust target weights (gently) to adjust for over/under diffraction during last iteration
6. Repeat until desired target agreement/efficiency is achieved or stagnation occurs

SGG Design Algorithm (cont.)

Algorithm strengths

+ Allows efficiency targets at multiple wavelengths in multiple diffraction orders
+ Can design arbitrary one-dimensional (1D) and two-dimensional (2D) reflection and transmission gratings
+ Maximum grating depth is a parameter in the design (can be more than one wave deep)
+ Good accuracy for large diffraction angles and wavelength ranges

Algorithm weaknesses

− Strictly valid only in scalar regime, but we have obtained surprisingly good results for small-period gratings

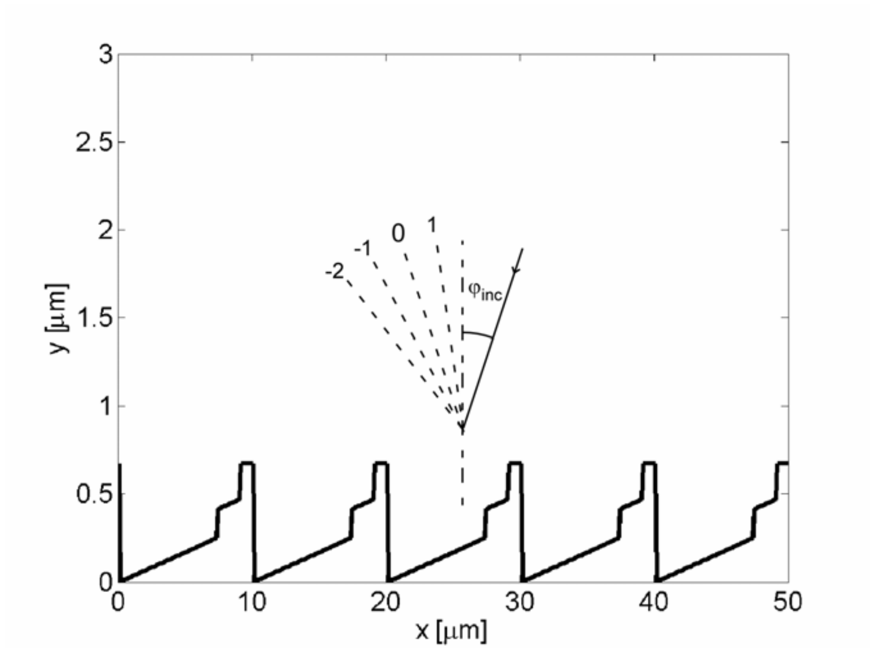
− Does not find the global optimum profile – we run multiple times with different random starting profiles and select most desirable

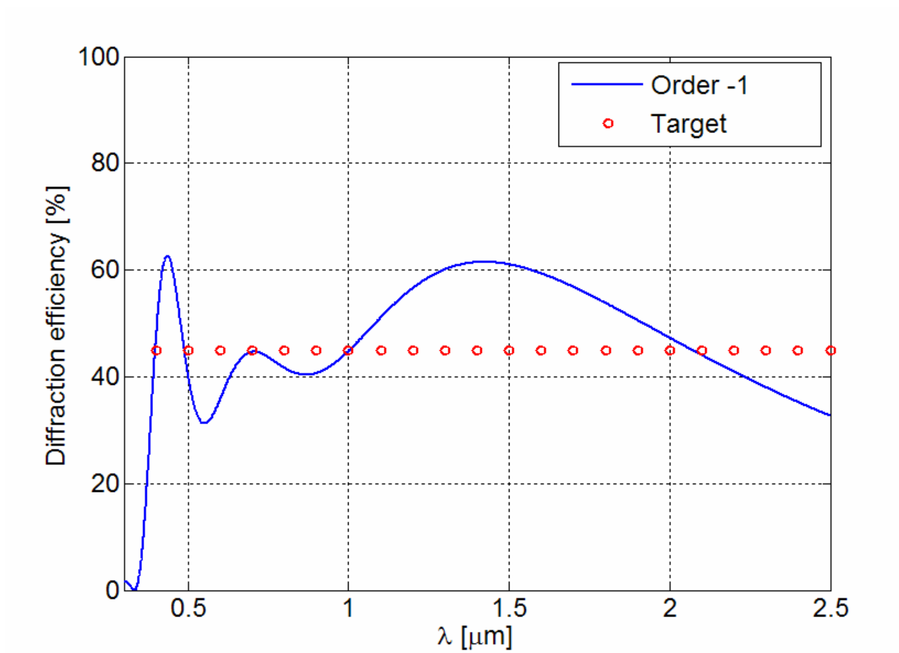
Broadband 1D Reflection Grating

Goal: Reflection grating having uniform efficiency from 400 to 2500 nm (-1 order)

Results

- Designed 10 µm period SGG using ORA with equal efficiency targets every 10 nm

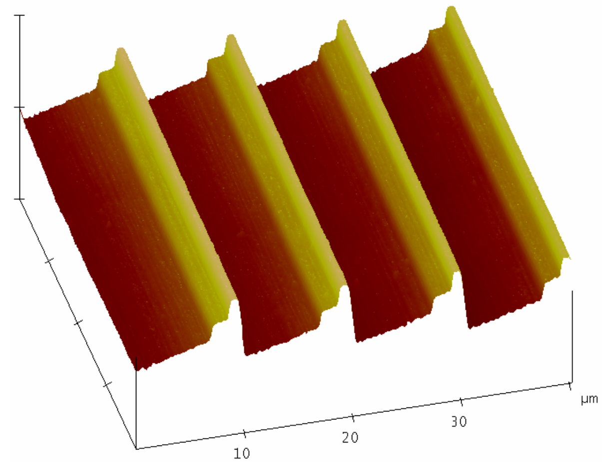


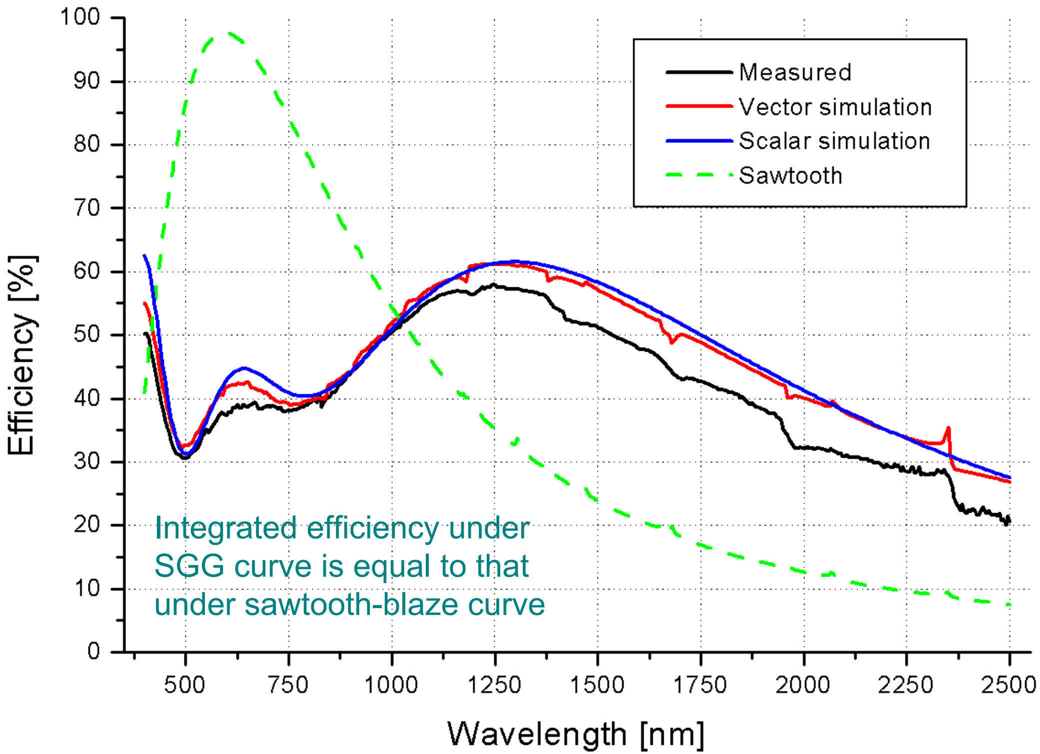


Broadband 1D Reflection Grating (cont.)

Results

- Fabricated grating in PMMA resist using direct-write E-beam lithography and overcoated with 60 nm of aluminum
- Simulated resulting profile using PCGrate vector electromagnetic software
- Measured diffraction efficiency (TE+TM)
  - Vectorial and scalar simulations agree well with experimental results
  - Wood's anomalies are seen in both the vector simulation (due to TM polarization) and the measurement



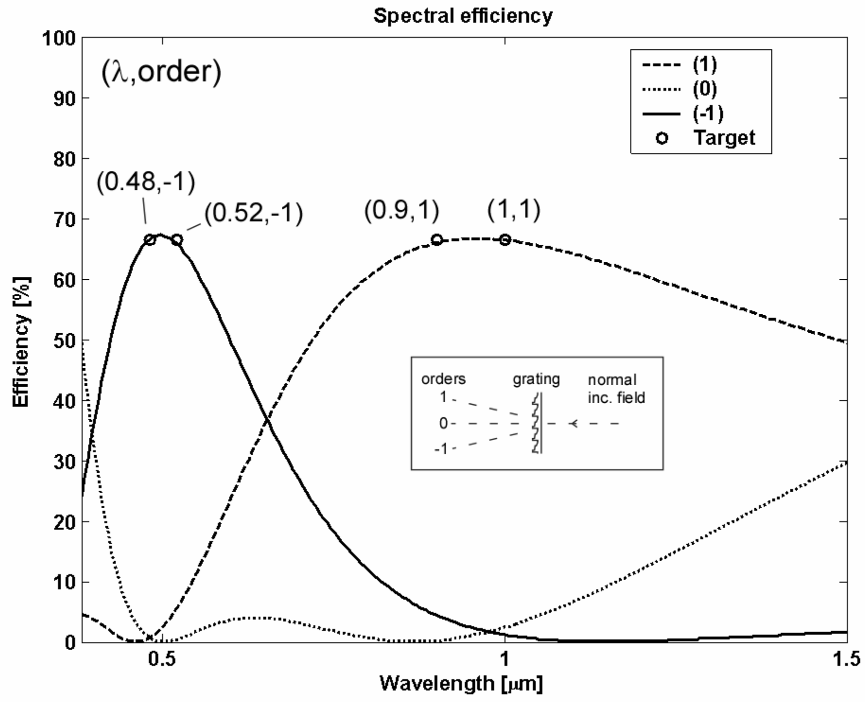


Small-Period 1D 2-Order Grating

Goal: Transmission grating having small (4 μm) period with targets in two diffraction orders (+1 and -1) at different wavelengths
→ Wanted to explore limits of scalar ORA design algorithm

Results

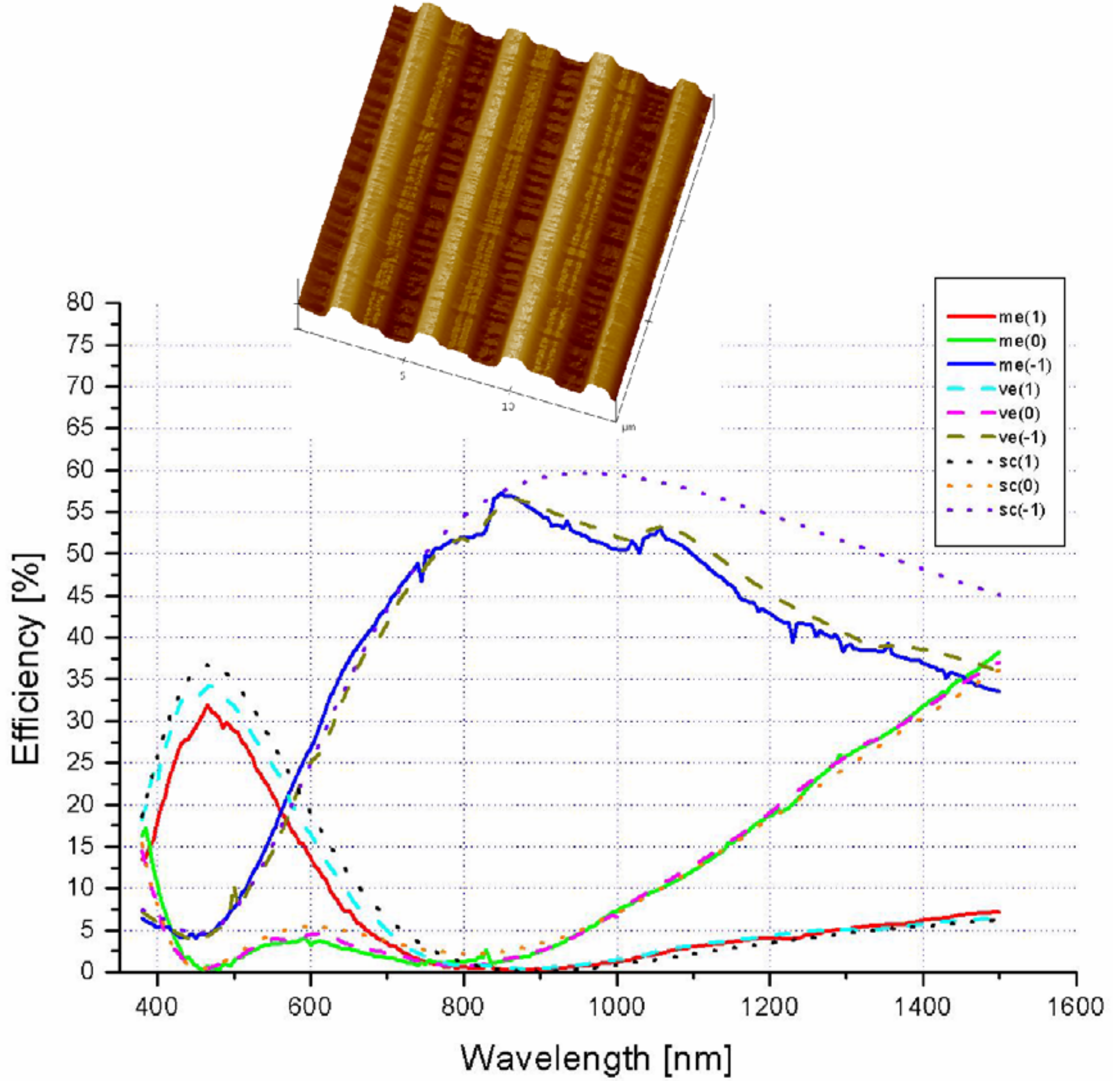
- Designed SGG using ORA algorithm with 4 targets at right
- Fabricated grating in PMMA using E-beam
- Measured surface profile of grating using atomic force microscope
  - Fabricated profile was slightly in error compared to design
  - Used measured profile for simulations



Small-Period 1D 2-Order Grating (cont.)

Results (cont.)

- Simulated fabricated profile using scalar and vector (PCGrate) models.
- The measured grating efficiency agrees well with the vector model while the scalar model is less accurate due to the small period / wavelength ratio.
- Surprisingly, scalar SGG design algorithm worked quite well even for fairly small periods.

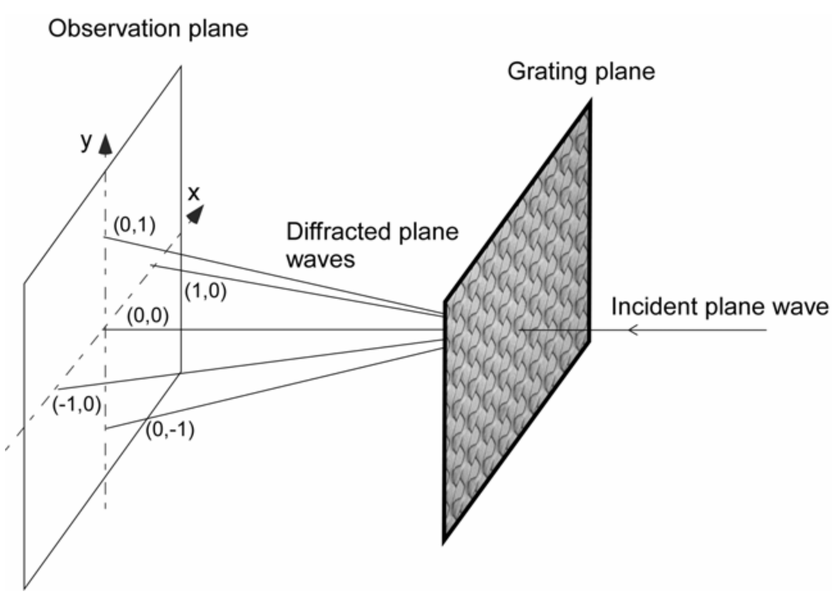


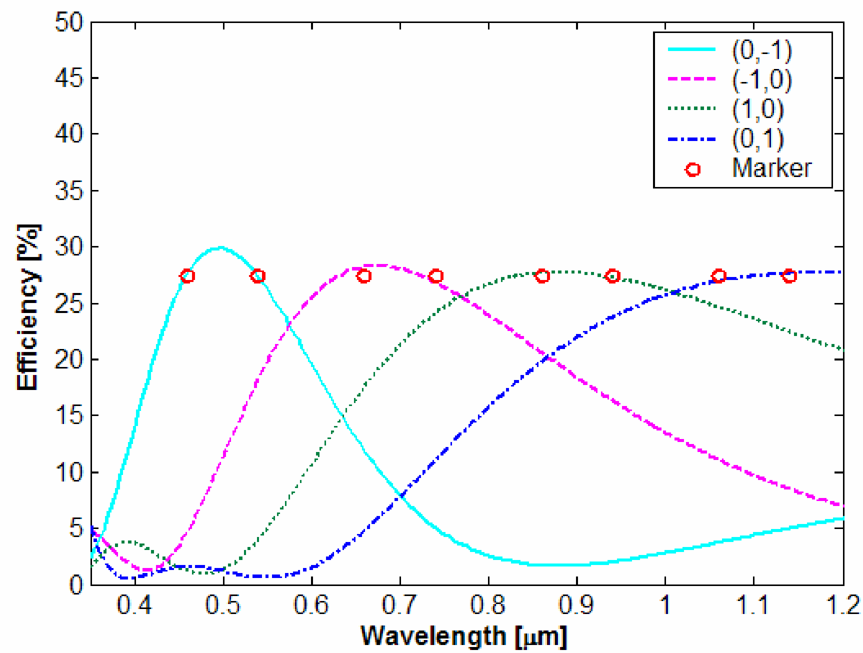
Two-Dimensional 4-Order Grating

Goal: 2D transmission grating with efficiency targets in 4 diffraction orders at 4 different wavelengths – useful for "computed-tomography imaging spectrometers" that utilize 2D gratings

Results

- Designed 2D SGG grating using ORA algorithm with targets in (1,0), (-1,0), (0,1) and (0,-1) orders at different wavelengths for each order

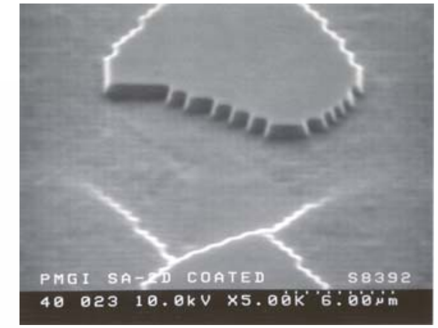


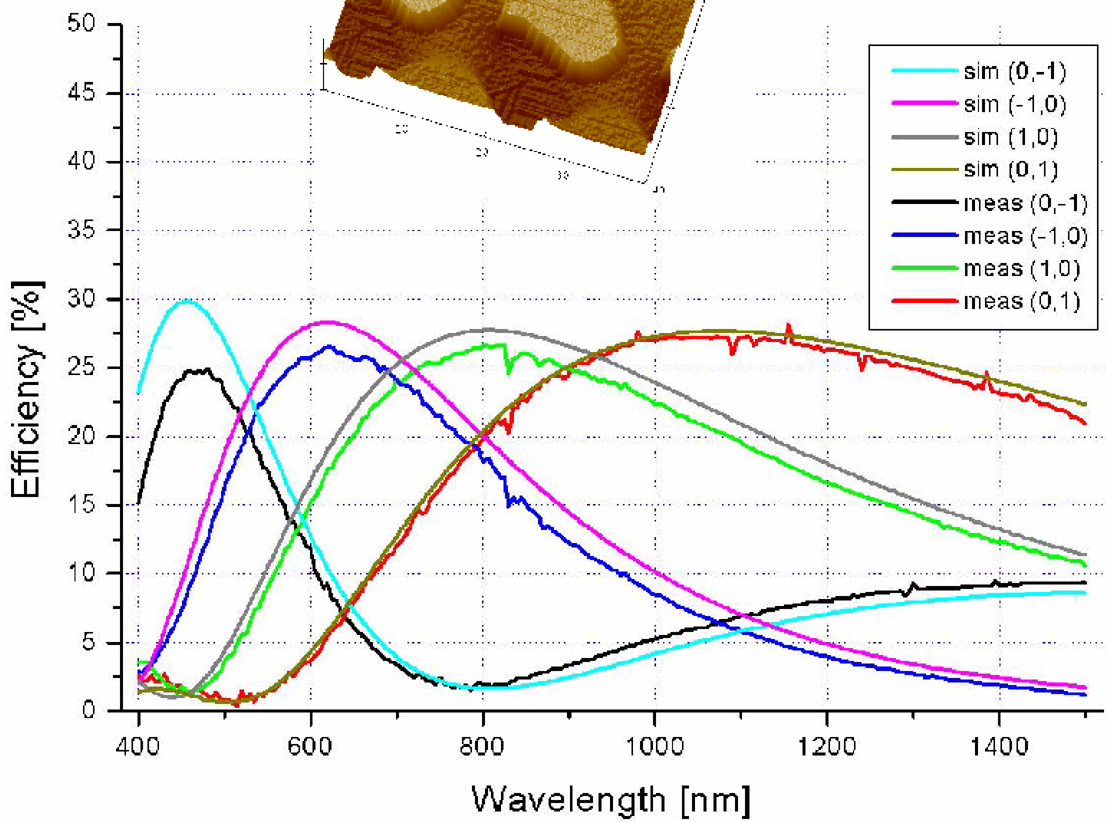


Two-Dimensional 4-Order Grating (cont.)

Results

- Fabricated the 2D SGG by E-beam, and measured the 4 orders of interest
  - Scalar simulations agree well with experimental results. (Vectorial simulations not available for 2D.)
  - Roughness scattering at short wavelengths may account for efficiency loss





Summary and Future Work

- ORA algorithm works well for designing 1D and 2D structured groove gratings
- Use scalar ORA groove design as starting point for other optimization algorithms (simulated annealing, genetic, etc.)
  - Contracted I.I.G., Inc. to develop console version of PCGrate-S (now available) to allow vector simulation of diffraction efficiencies inside a groove-profile optimization
  - Would allow separate targets for TE and TM polarization to minimize (or maximize) polarization dependence