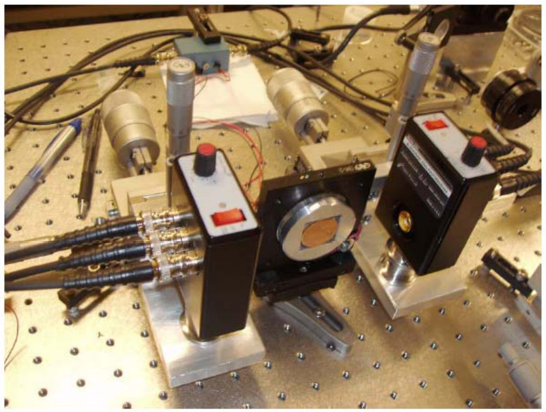
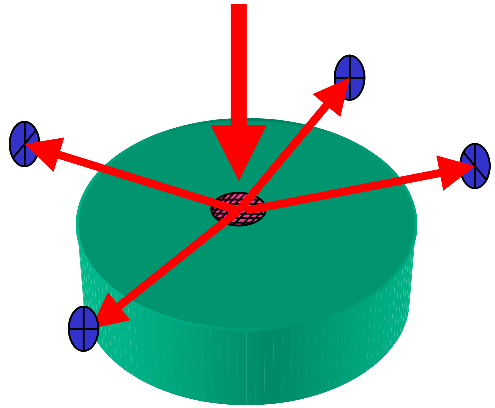
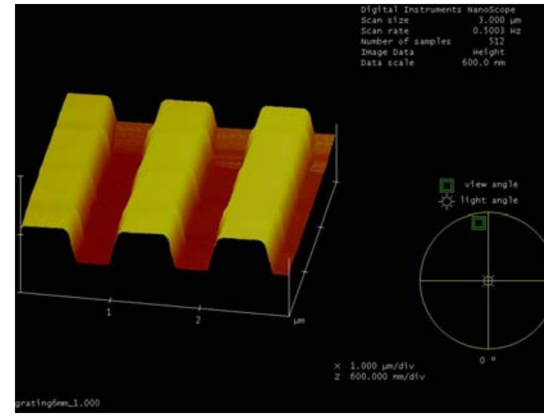
Progress in Grating Optical Sensors for Gravitational Wave Detection







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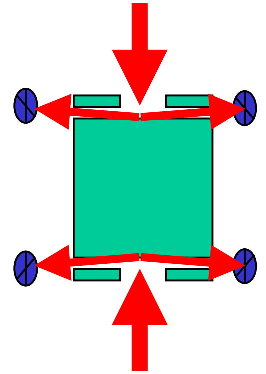
Stanford University

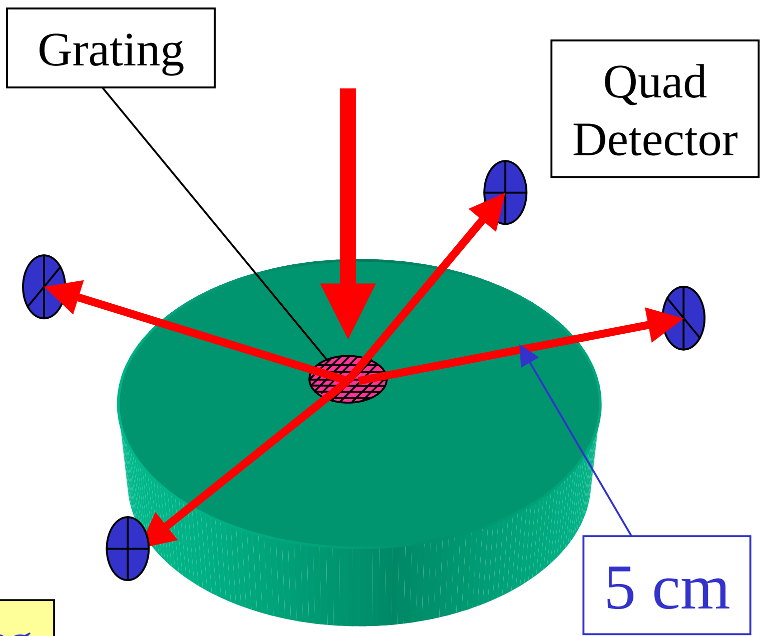
LIGO Science Collaboration (LSC) Meeting
Joint Meeting of Optics and Suspension Working Groups
LIGO Hanford Observatory, March 22, 2006

Grating Angular Sensor

No Transmissive Optics Components: Enhanced Thermal Stability
No Additional Optics: Enhanced Signal Integrity

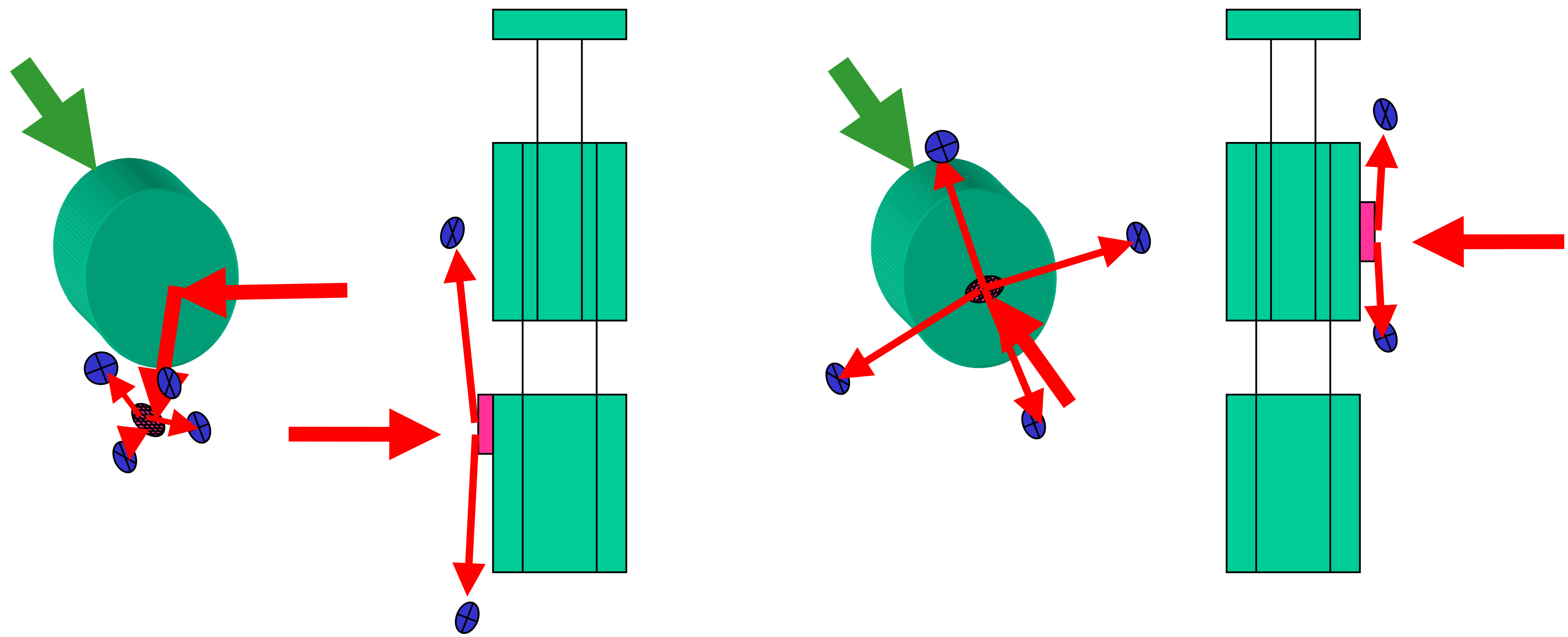


- Grating angular sensor
  - Grating can magnify the angle without using a telescope
  - Grating can compress the beam cross section without using a focusing lens
  - Simultaneously extract pure rotational and displacement signal
  - Compact size with short working distance (5cm in lab test)
  - No optics between the reflection surface and the quad photodiode
    - More stable?



5-port Grating Configuration

Possible LIGO Installations Options



Tilted Illumination

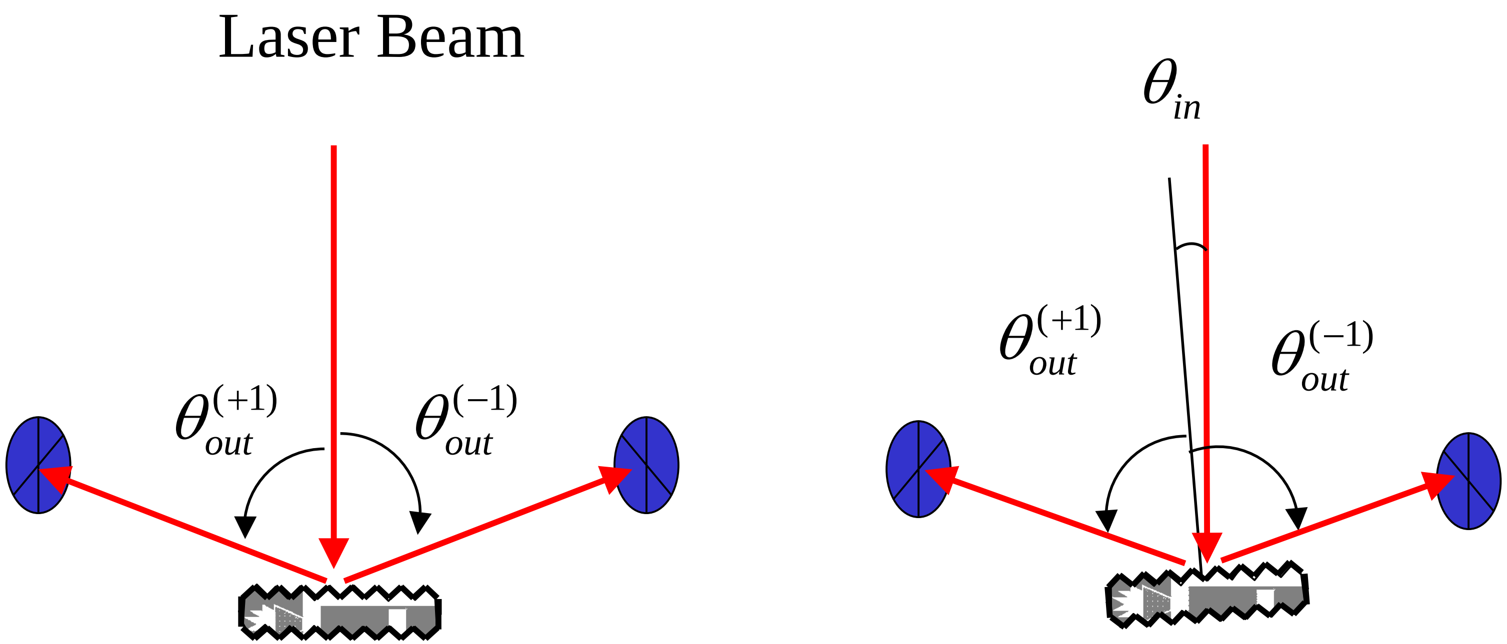
Main test mass

Back of the high reflectors

Intermediate test mass

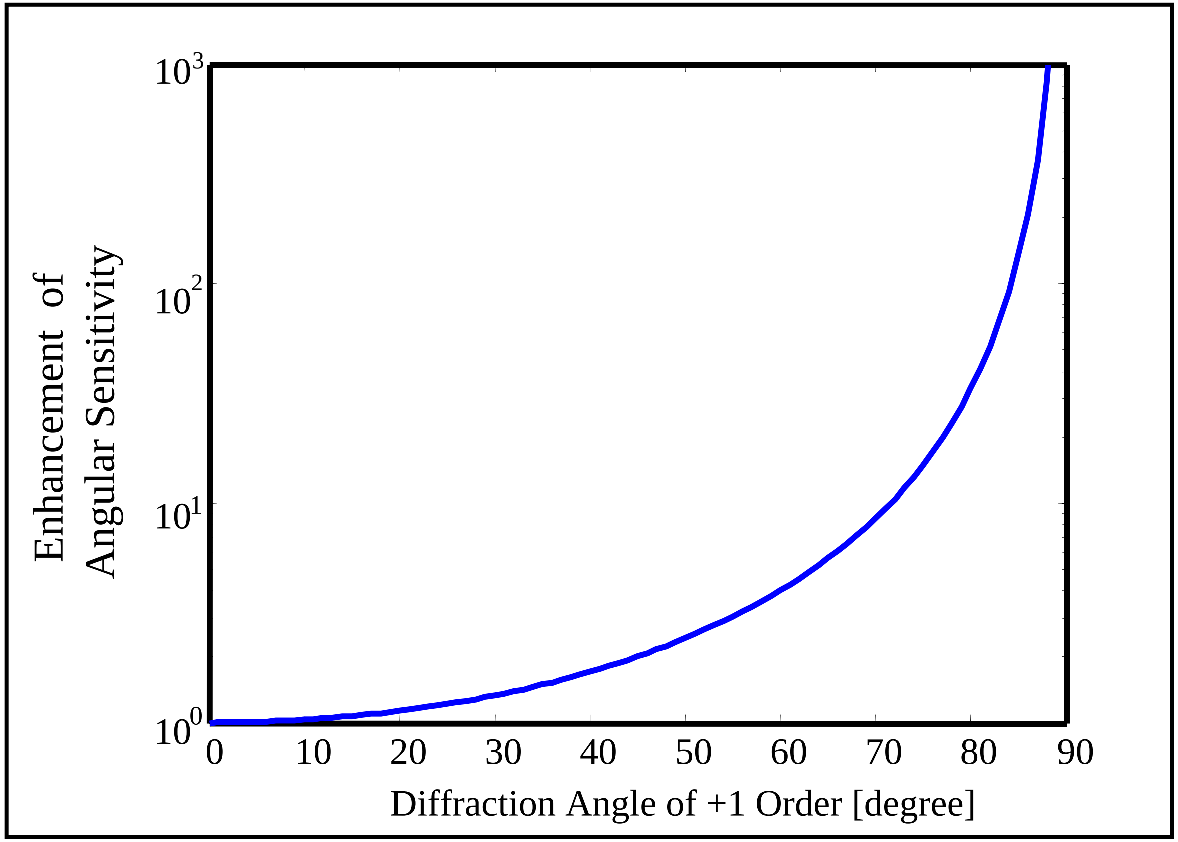
Or suspension point interferometer

Grating Based Angular Sensor
Diffractive Angular Interferometry



$$d\left(\sin\theta_m - \sin\theta_{in}\right) = m\lambda$$

Overall Enhancement of Angular Sensitivity



- Grating angle amplification

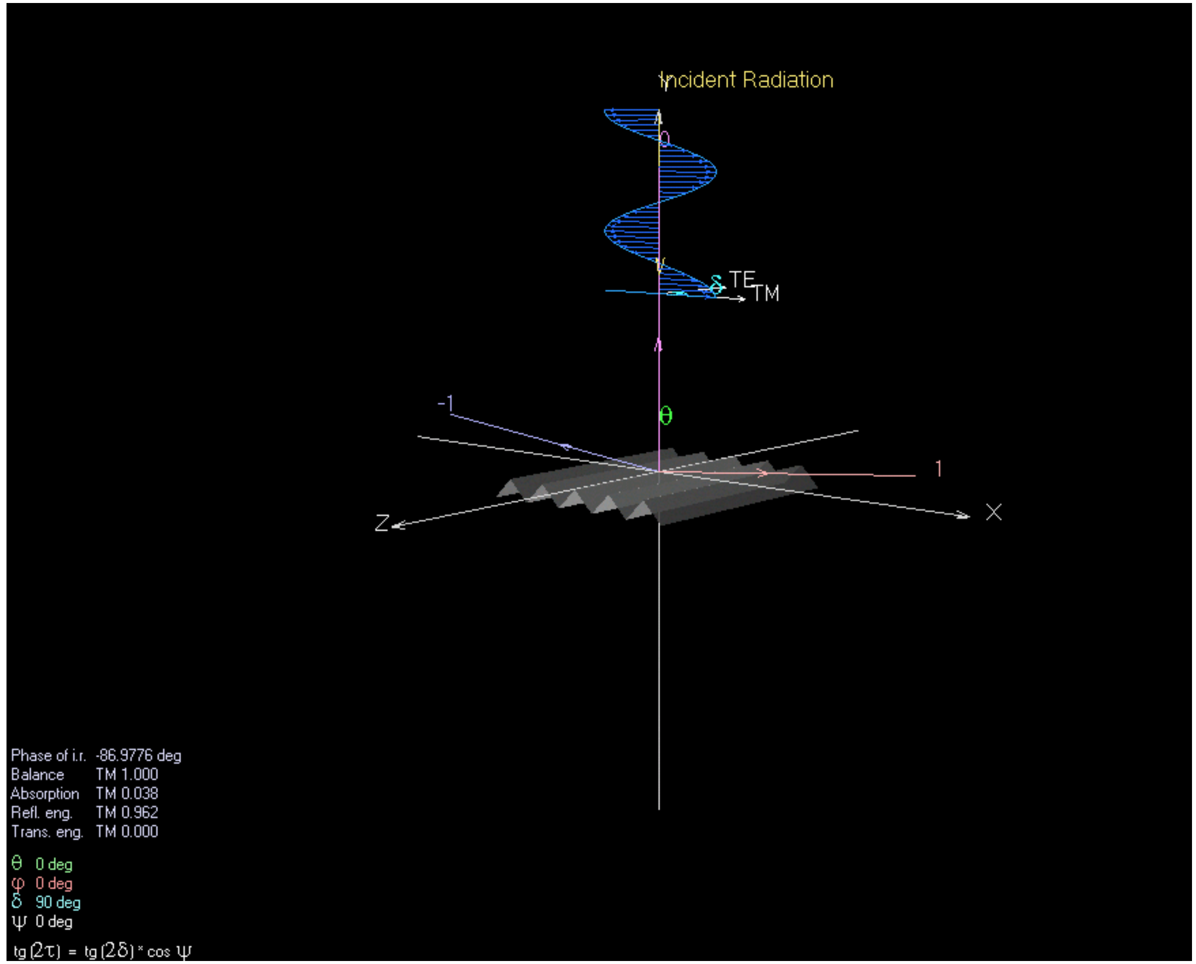
- Beam cross section compression

$$P_m = K'\left(\frac{\cos(\theta_{in})}{\cos(\theta_m)}\right)^2 P_{in}$$

K. Sun, S. Buchman, and R. L. Byer, "Grating Angle Magnification Enhanced Angular and Integrated Sensors for LISA Applications," accepted for publication at J. Phys. C. Special issue of Almadi 6 Conference on Gravitational Waves

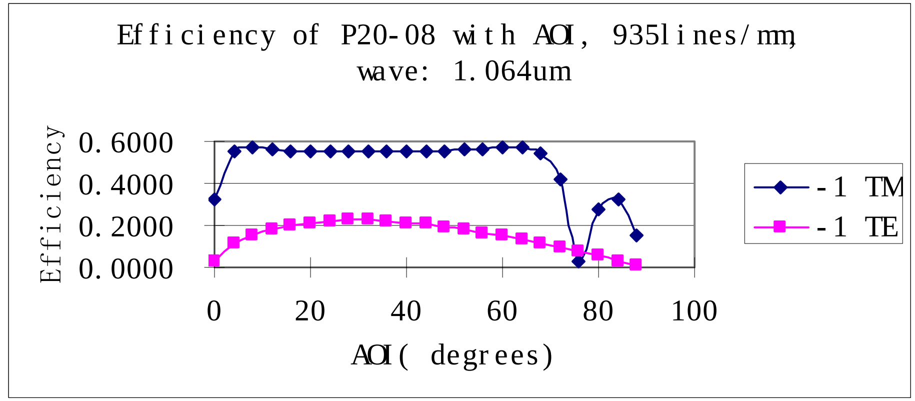
Grating Design Configuration

- Normal incidence
- TM mode (E-vector perpendicular to grove directions
- Density 933~935 lines/mm
- Wavelength 1064 nm



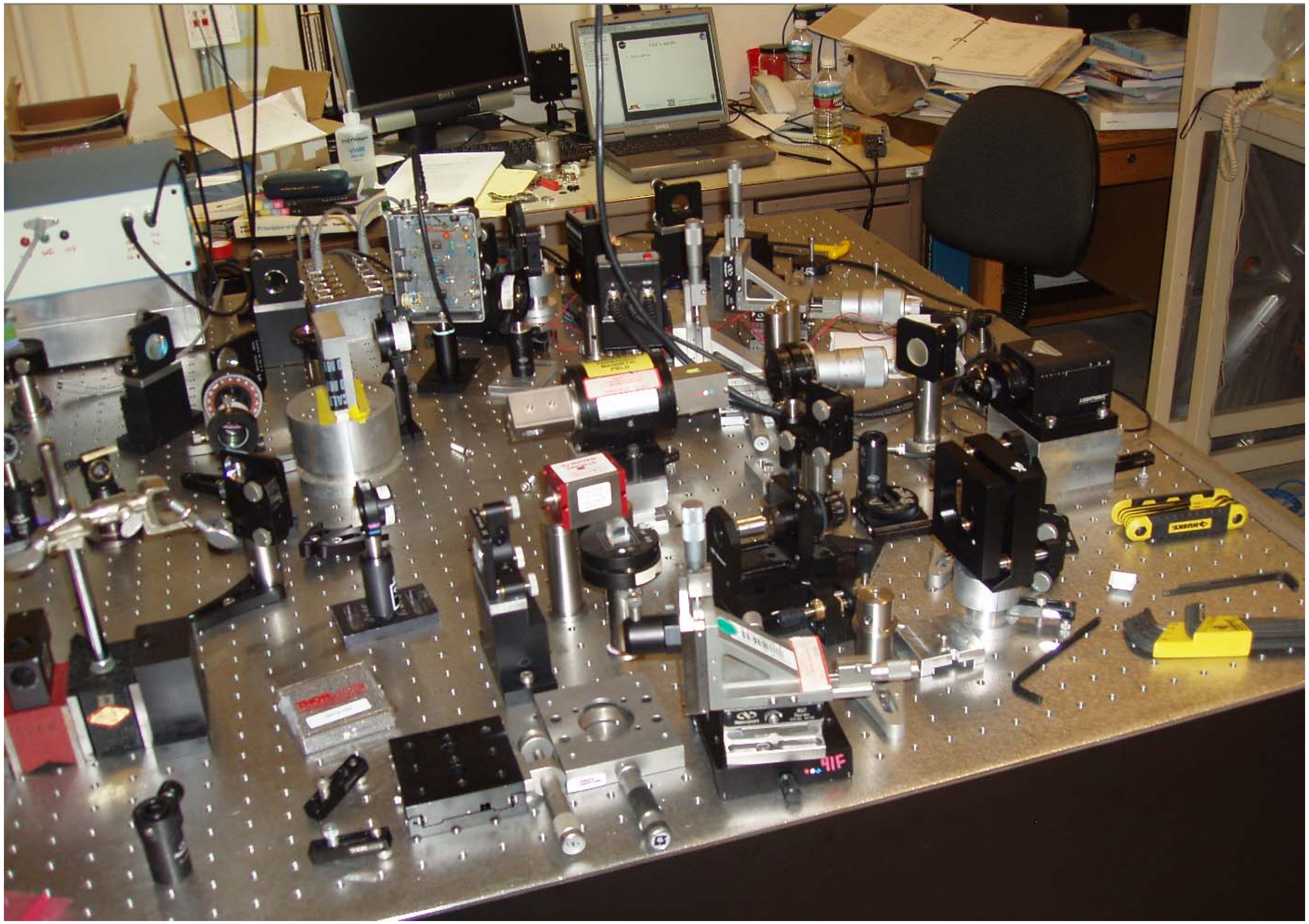
Grating Profile and Diffraction Efficiency

- Holographic grating
- Sinusoidal profile
- Density 933~935 lines/mm
- Wavelength 1064 nm

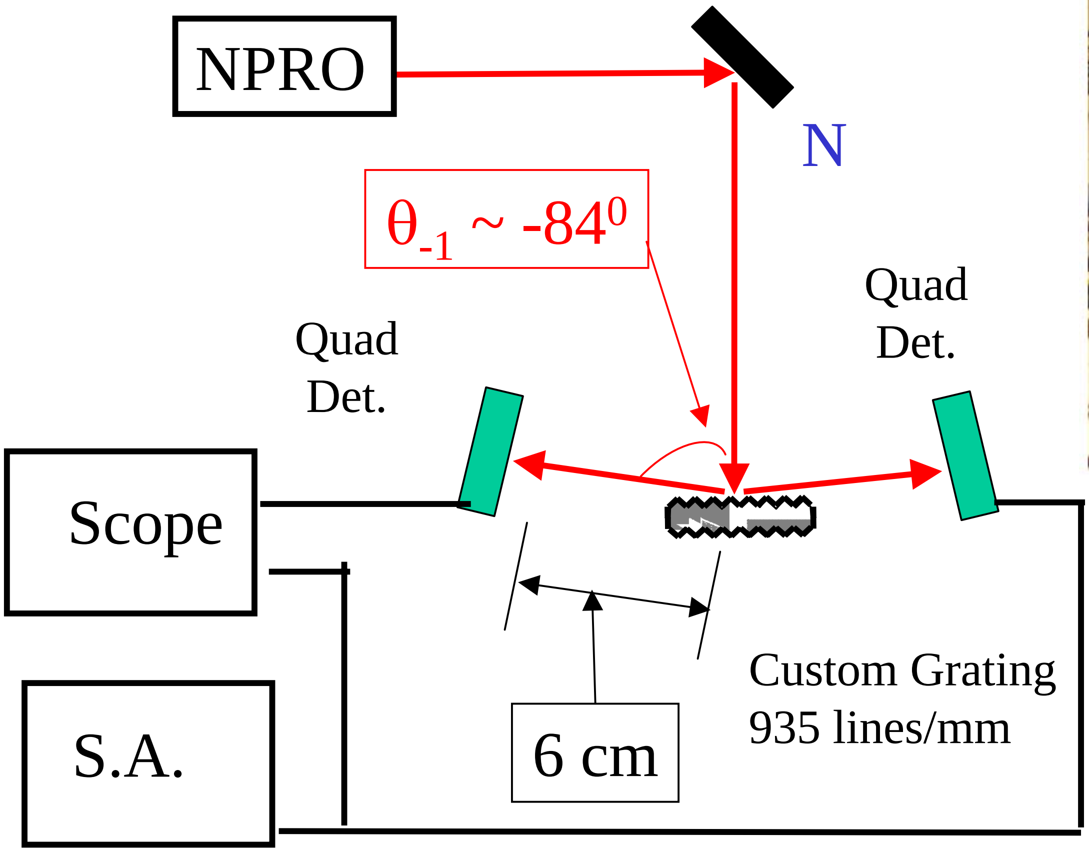


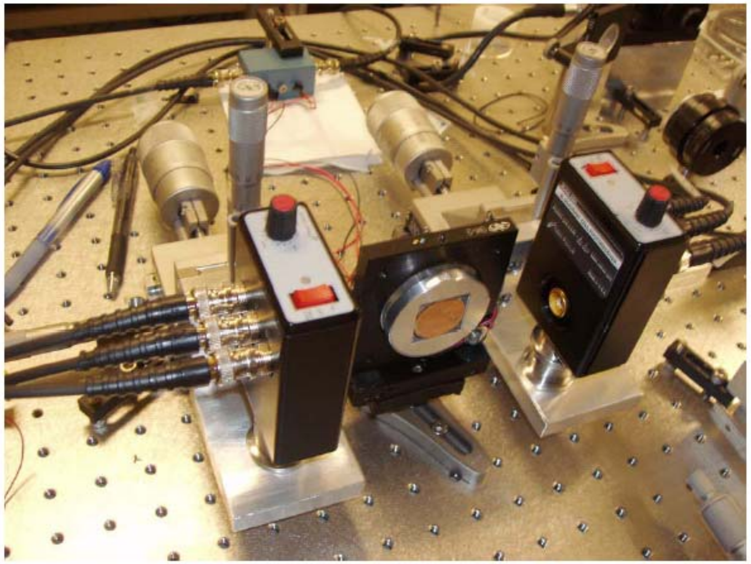
Order #	Eff.	Eff.(TM)	Phase TM	Ampl.TM	Diffr. angl	Az. angle	Polariz. angle, deg	
1	0.29809	0.29809	96.26951	1.722202	84.23187	0	90	
0	0.365359	0.365359	128.0311	0.604449	0	0	90	
-1	0.29809	0.29809	31.32713	1.722202	-84.2319	0	90	

Experimental Setup



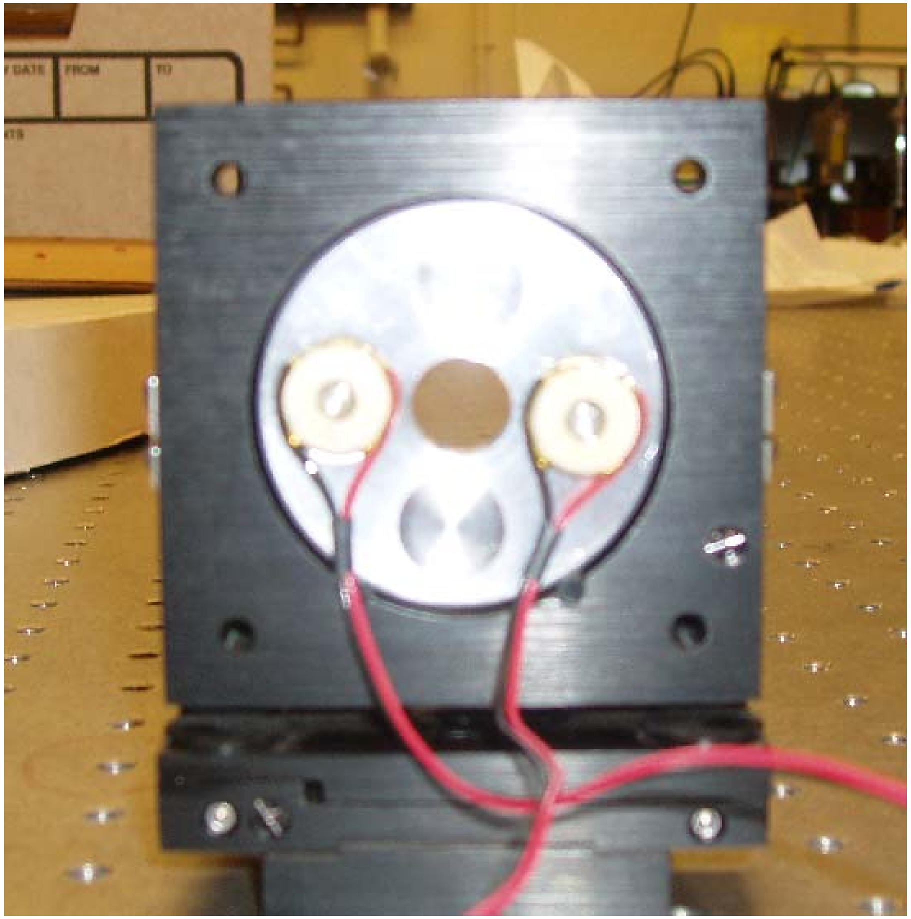
Recent Grating Angular Sensing Experiment with Two Detectors

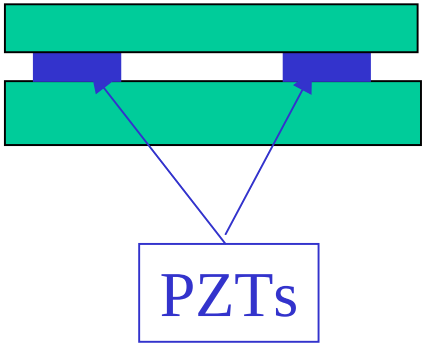




- **Simple construction**
- **No extra optics**
- **No other uncertainty and noise**

Angular Motion Control





Excursion: ~0.5 μm/100V

Signal Spectrum for 10 nm, 0.5 μrad Angular Drive

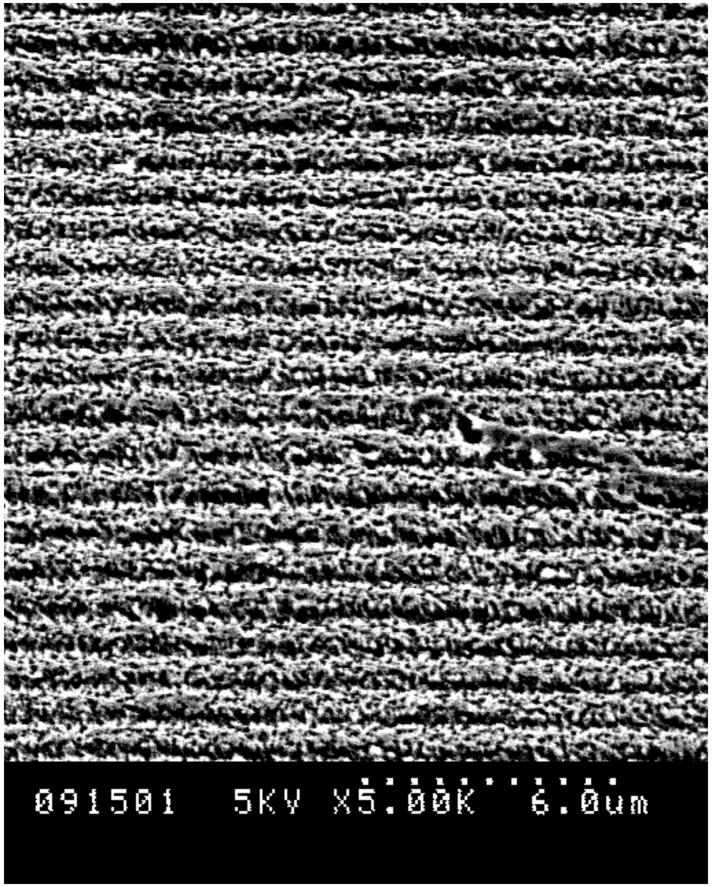
- Differential drive of two PZTs with oscillatory voltages of opposite phase (~2V)
- PZT displacement 10 nm
- Grating rotation 0.5 μrad
- SNR ~42 dB
- Noise floor level ~4 nrad
- Estimate of 3 dB SNR sensitivity: 8 nrad/$Hz^{1/2}$

Grating Fabrication Approaches

- Electron-beam lithographic techniques for dielectric gratings
- Trans-Imprinting for metallic gratings
  - Transference of pattern from dielectric to gold coatings via imprinting
- Focused Ion Beam
  - Using Ga^{+} ions to mill gold or dielectric directly
- Ion etcher (Collaboration with LLNL)
- Laser machining

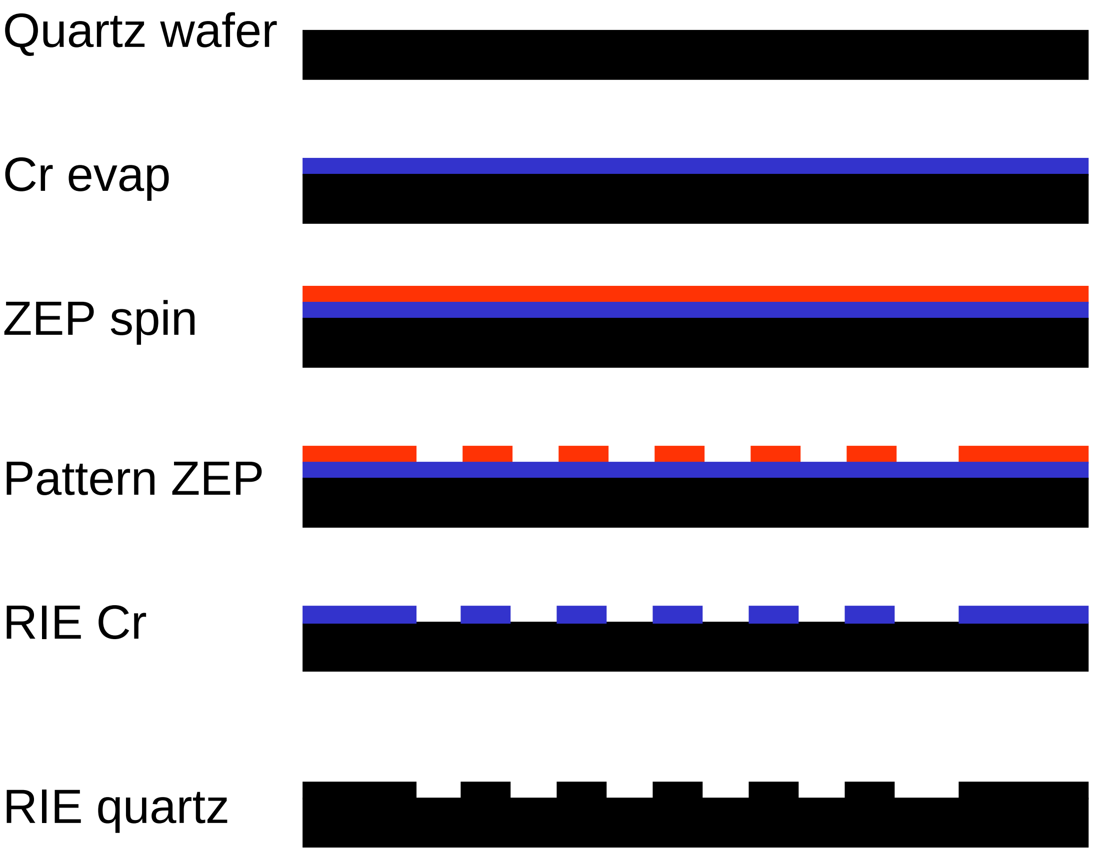
Dielectric grating fabrication (initial attempt)

- Similar to recipe on last slide, except that chrome is patterned with lift-off.
- Poor adhesion between resist and quartz lead to inaccurate liftoff
- Surface roughness from non-optimized gas concentrations

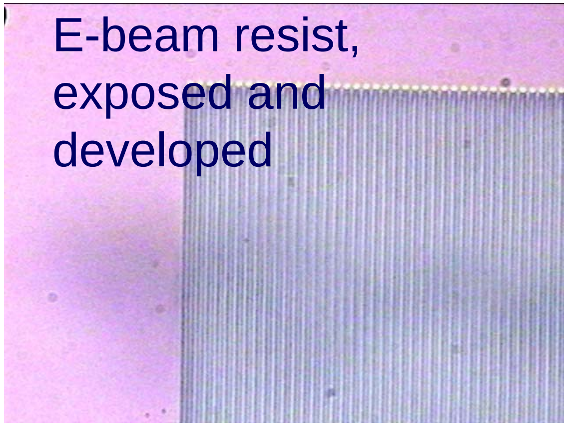


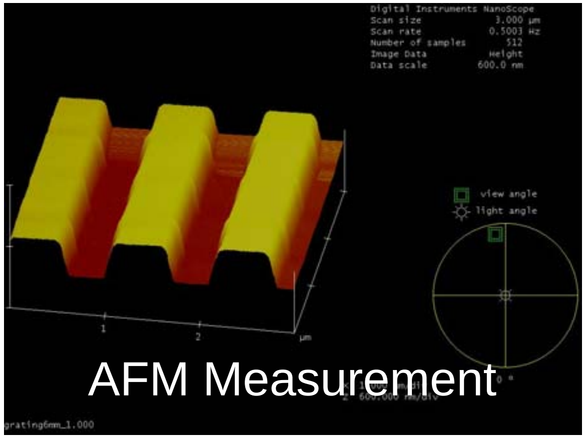
Dielectric grating fabrication

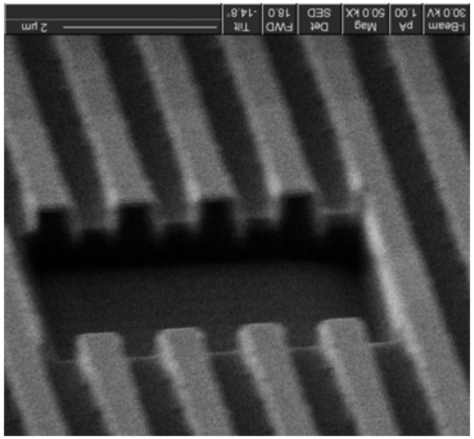
- Approach: fabricate gratings in dielectrics first, then transfer them to the proof mass materials.
- Use e-beam litho because of its flexibility compared to other methods
  - Flexibility needed when making 2d patterns



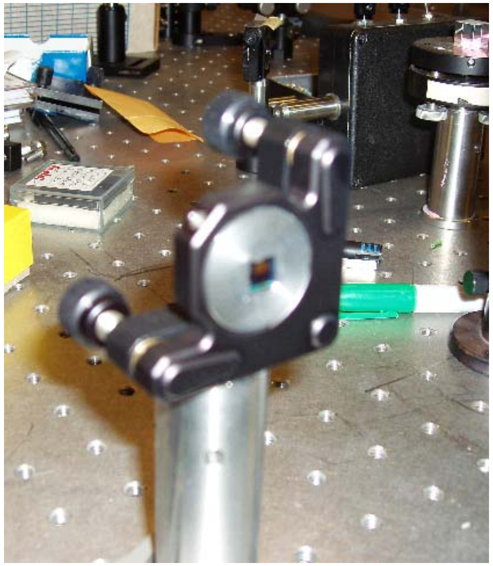
Dielectric Grating Fabrication
- improved results -





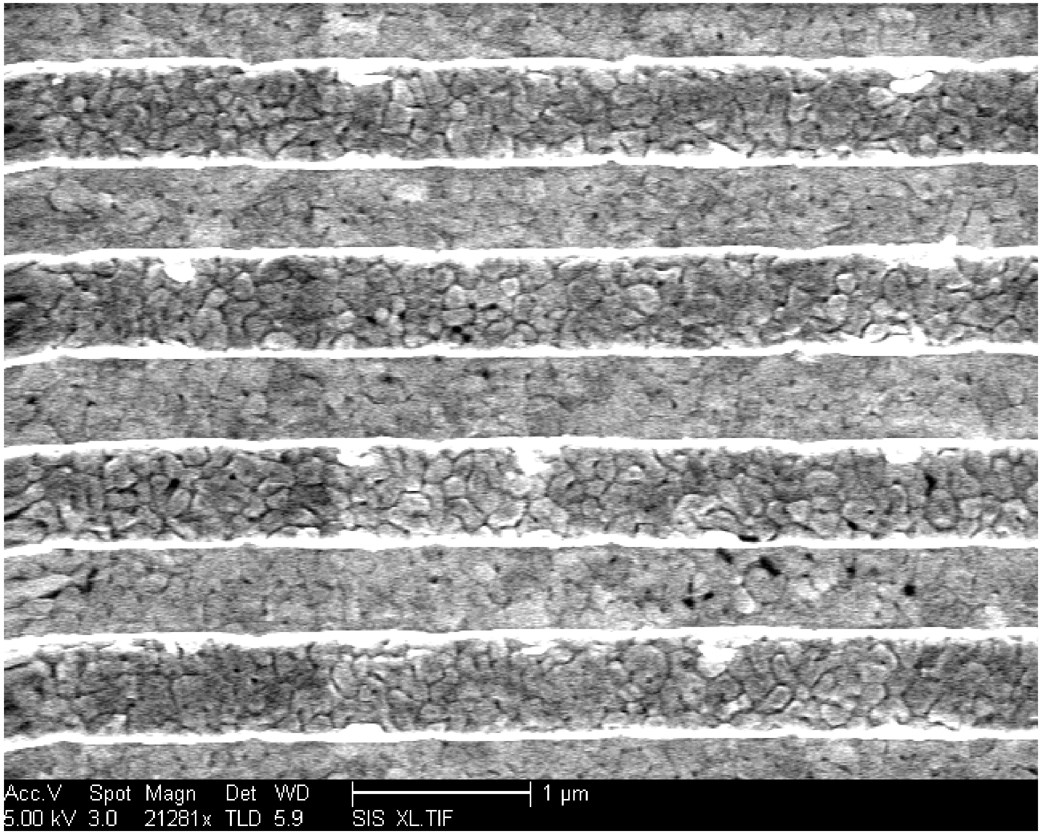


- High quality dielectric grating fabricated with proper height (as confirmed by AFM and SEM inspection).
- Cross-sectional view confirms rectangular profile.



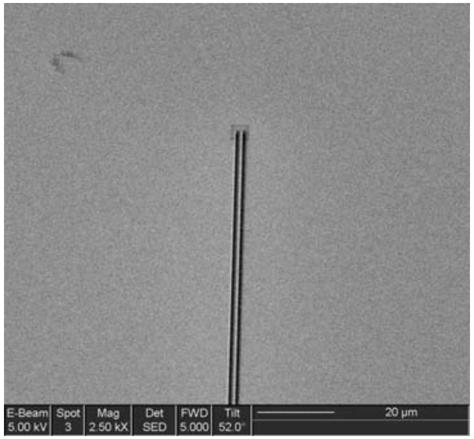
Trans-Imprinting Trial Successful

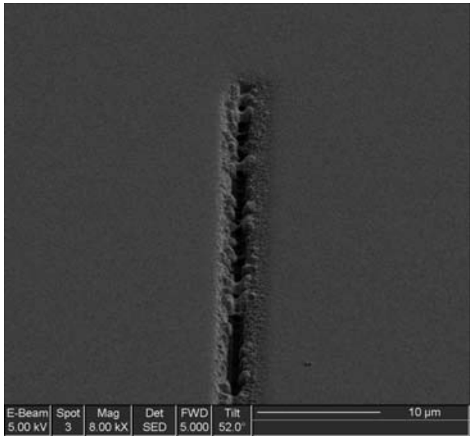
- Initial trial succeeded in making a grating pattern in gold.
- Performed at 1 GPa
- Using cited numbers of 250 MPa yield stress, required force for 2mmx2mm grating is 113 lbs.
- SEM shows the grain boundaries of the gold.
- Still remains to be determined how much force proof mass can sustain.



Focused Ion Beam

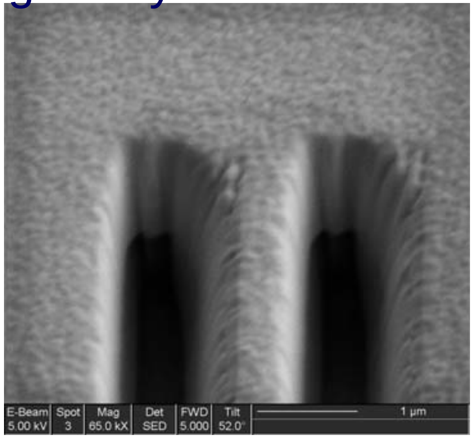
- As proof of principle, milled 1µm lines with Ga^{+} ions
- Used FEI Strata 235DB dual-beam FIB/SEM
- 3000pA and 20,000pA apertures used.
- Smaller current produced more accurate lines
- An estimated 5.6 hours for 1mmx1mm grating
- Improvements in the future:
  - Dose optimization for depth control
  - Finer steering of ion beam

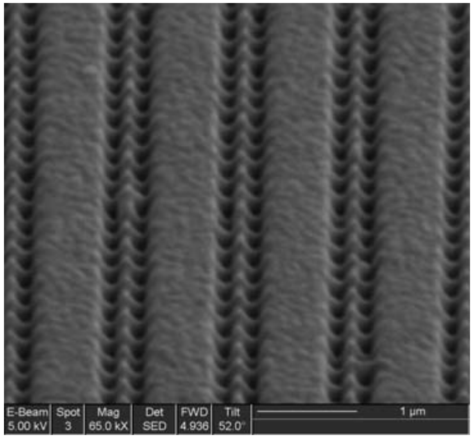




3000 pA, punched completely through gold layer

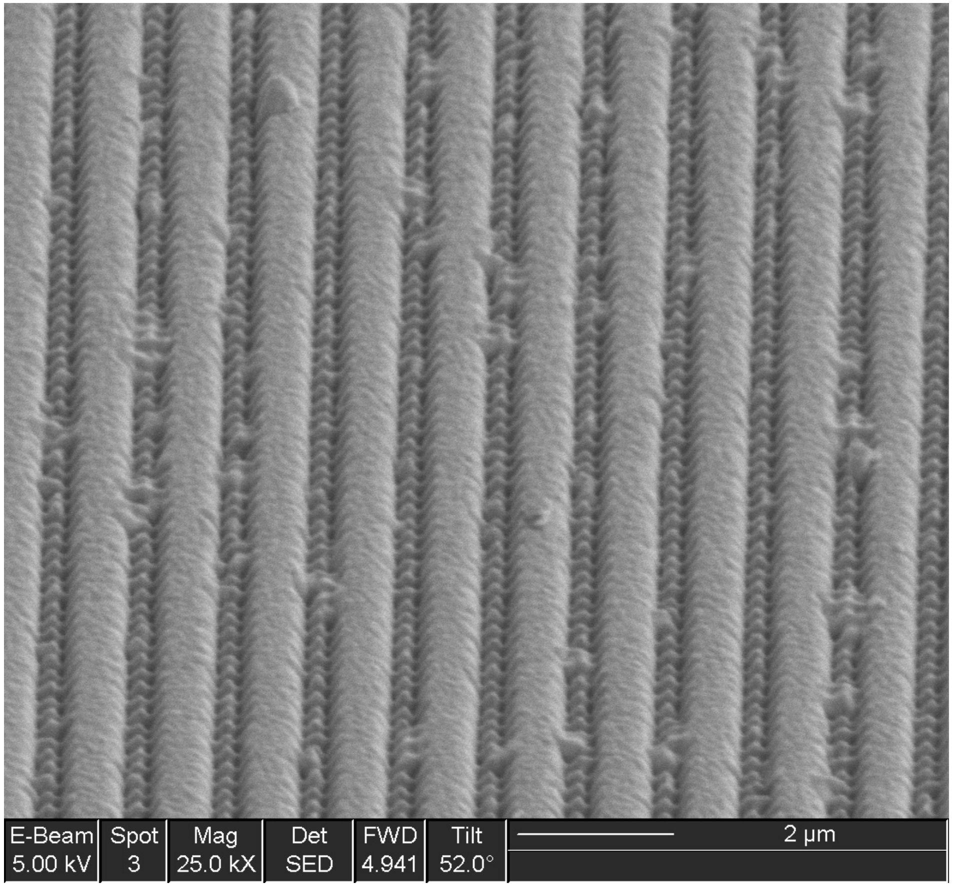
20,000 pA, jagged edges



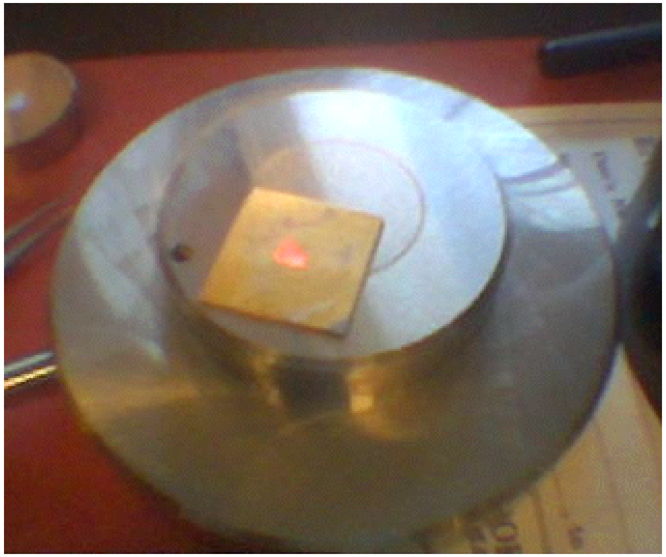


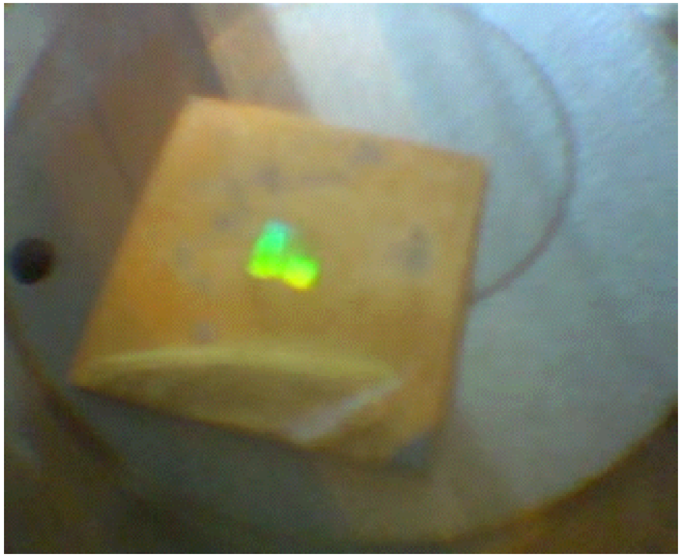
Focused Ion Beam Etching Getting Real

- Optimizations in
  - Beam current
  - Pixel size
  - Etching time
- Has a hope to be a viable way of grating fabrication for sensor applications



Grating by Trans-Imprinting





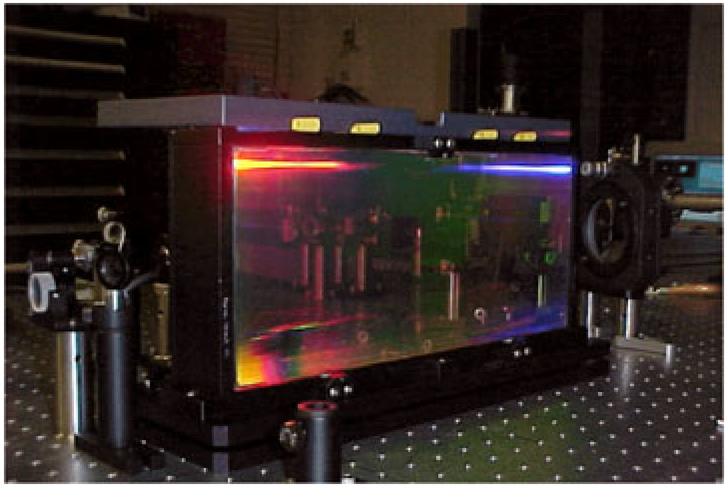
- Grating on Au can be directly imprinted using quartz dielectric grating
- Grating on Au coated W substrate (may have LISA applications)

Collaboration on Diffractive Optics with Lawrence Livermore National Laboratory

Collaborative Research Highlight

- LLNL is the primary center of design and fabrication of high quality dielectric gratings due to NIF application

- The Stanford/LLNL collaboration strongly favors Stanford research
  - LLNL will supply high quality dielectric gratings to Stanford LIGO and LISA programs
  - LLNL sponsors a Stanford graduate student
  - Stanford will characterize gratings for LLNL, LIGO and LISA applications, and provide data to LLNL



JPL DRDF Program

Sponsored Research Highlight

- Grating angular sensor is the subject, supporting a full time grad student
- Program execution
  - Majority of the deliverables made within only six months
  - Spending rate is on target
- Excellent progresses in achieving deliverables
  - Diffraction orders at large diffraction angle demonstrated
  - Specialty 935 lines/mm gratings design verified
  - Angular sensitivity reaches 4 $nrad/Hz^{1/2}$, far better than requirement of 100 $nrad/Hz^{1/2}$
  - Dielectric grating fabrication succeeded
  - Feasibility of grating marks on Au surface demonstrated with a variety of methods
- Publications
  - First paper accepted for publication at JPCS
    - "Grating angle magnification enhanced angular sensor"
  - Submissions scheduled for LISA 6th Symposium

Conclusion

- Compact angular sensors for possible LIGO interferometer control applications
- Two-sided detection scheme will provide pure rotation measurement
- Lithographic Techniques for dielectric gratings
  - High quality dielectric gratings fabricated
- Imprinting
  - Demonstrated viable grating transfer process
- Focused Ion Beam
  - Proved feasibility of patterning grating on gold surface

Acknowledgements

- Support for this project comes from
  - NSF LIGO for gravitational wave detection
  - JPL DRDF for precision angular sensing