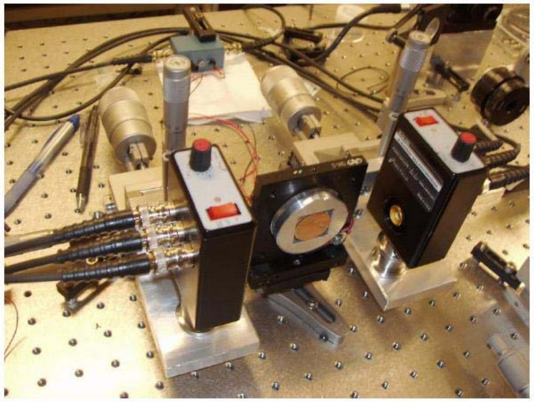
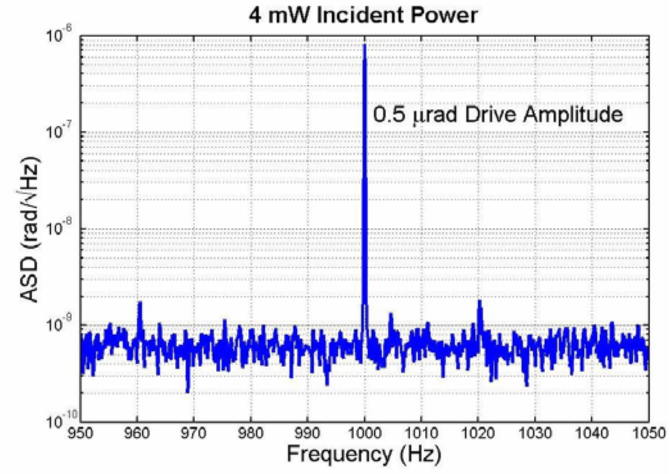
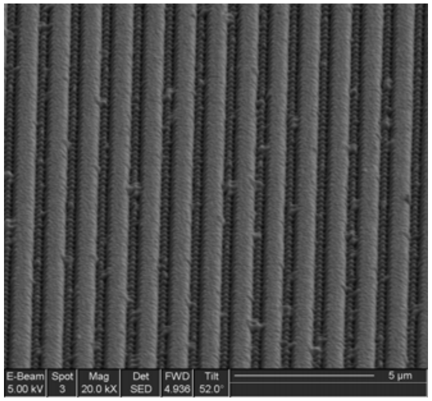
A Symmetric, Robust Grating Angular Sensor for LIGO Sensing and Control





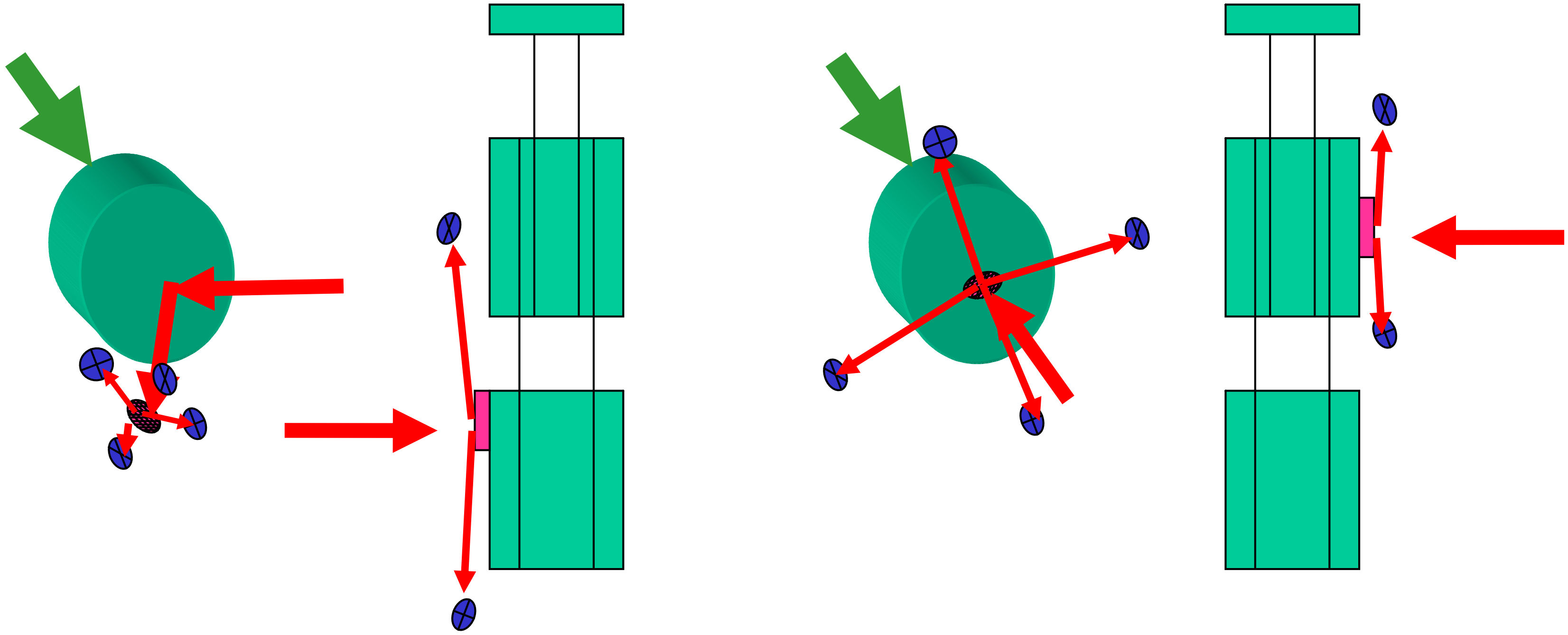


Ke-Xun Sun, Patrick Lu, and Robert Byer
Stanford University

LIGO Science Collaboration (LSC) Meeting
Louisiana State University
August 16, 2006

LIGO-G060485-00-Z

Possible LIGO Installations Options



Tilted
Illumination

Main test mass

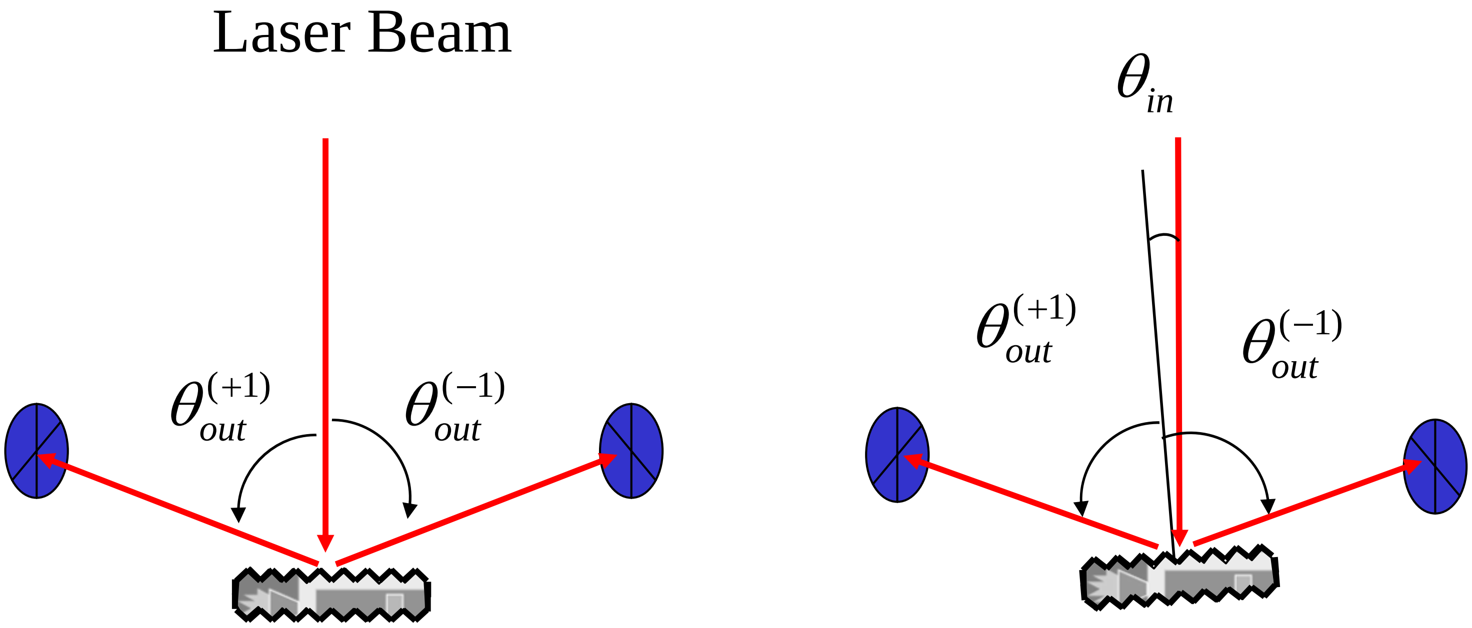
Back of the high
reflectors

Intermediate test mass

Or suspension point
interferometer

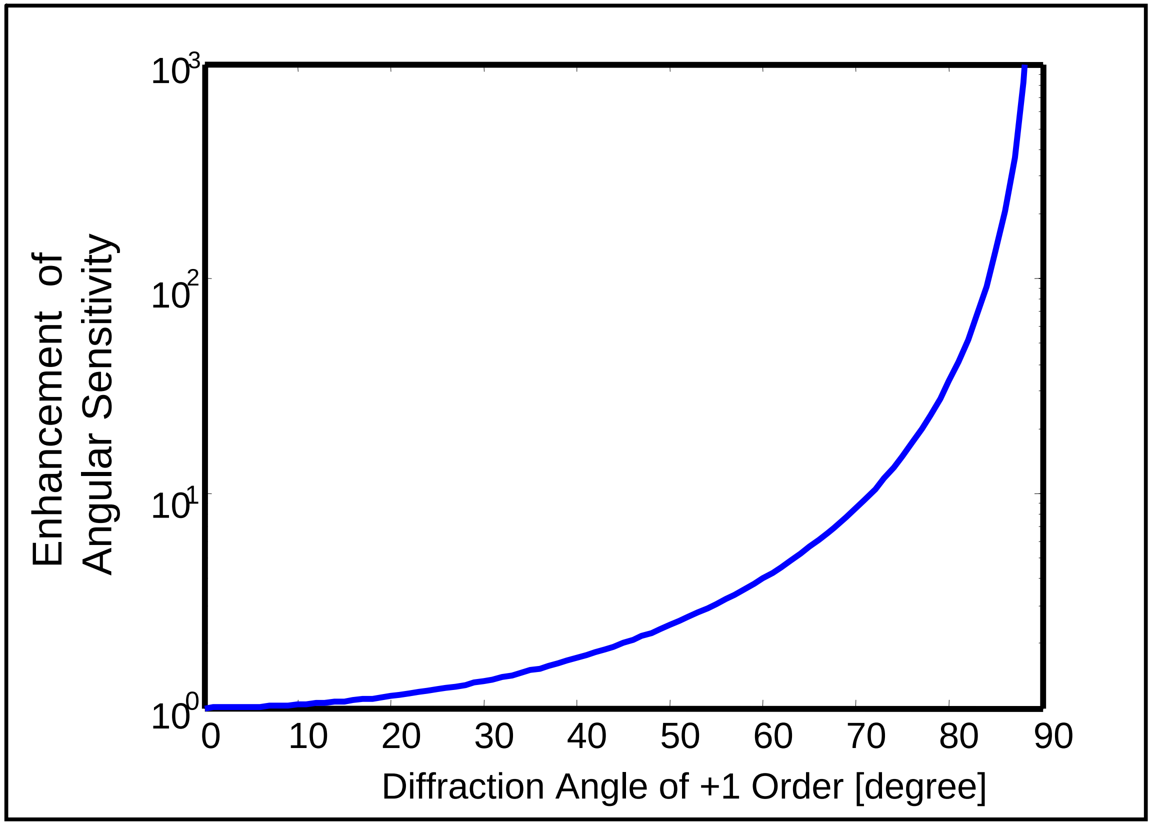
Grating Based Angular Sensor

Sensitive to Differential Movement of the Diffracted Beams



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

Overall Enhancement of Angular Sensitivity



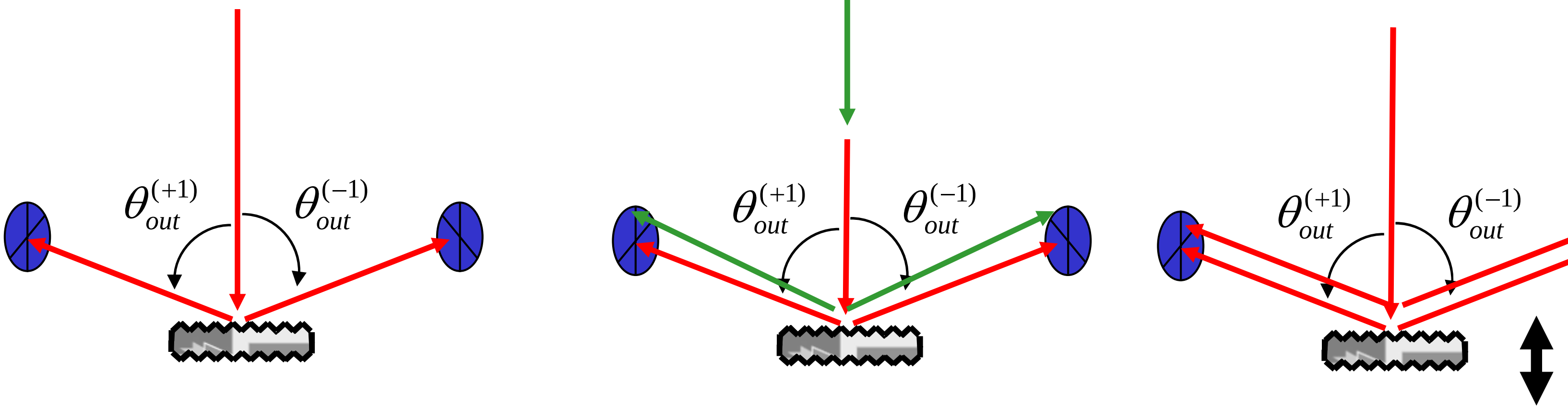
- Grating angle amplification

- 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

Robustness of the Symmetric Grating Angular Sensor



Laser Beam

Laser Frequency Variation Δν

Pure Rotational Measurment

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

$$\Delta\theta_m = \left(\frac{Nm\lambda^2}{c}\right)\frac{\Delta\nu}{\cos\theta_m}$$

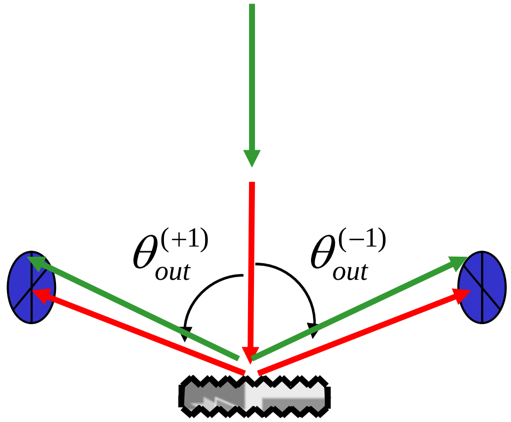
Grating Displacement

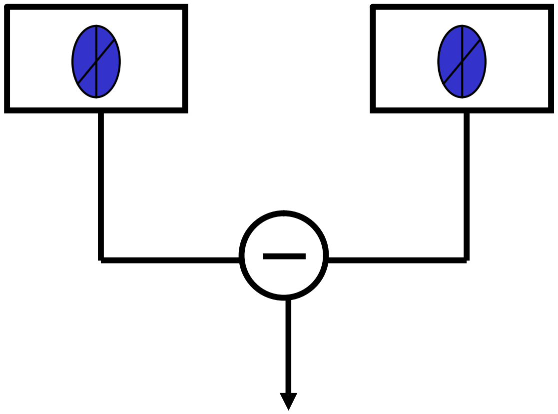
Δν induced angular movement also magnified by grating

Common Mode Rejection to Reduce the Laser Frequency Noise Effect

(Angular Signal Doubled)

Laser Frequency Variation Δν





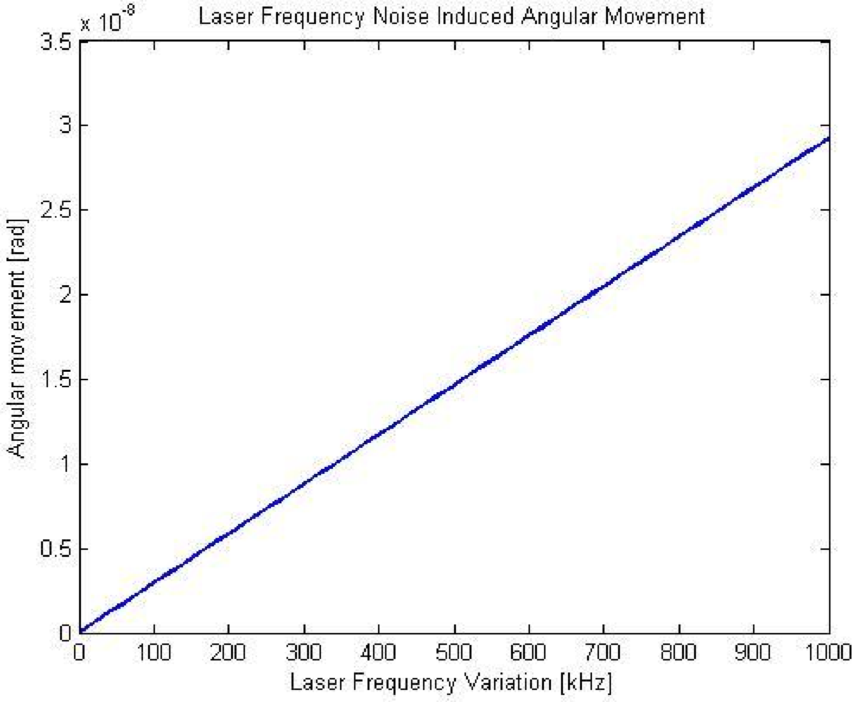
$$\left(\Delta\theta_{+1}-\Delta\theta_{-1}\right)=\mathrm{CMRR}\times\left(\Delta\theta_{\pm1}\right)$$

$$I\left(\Delta\theta_{+1}-\Delta\theta_{-1}\right)=\mathrm{CMRR}\times I\left(\Delta\theta_{\pm1}\right)$$

Common mode rejection also works for

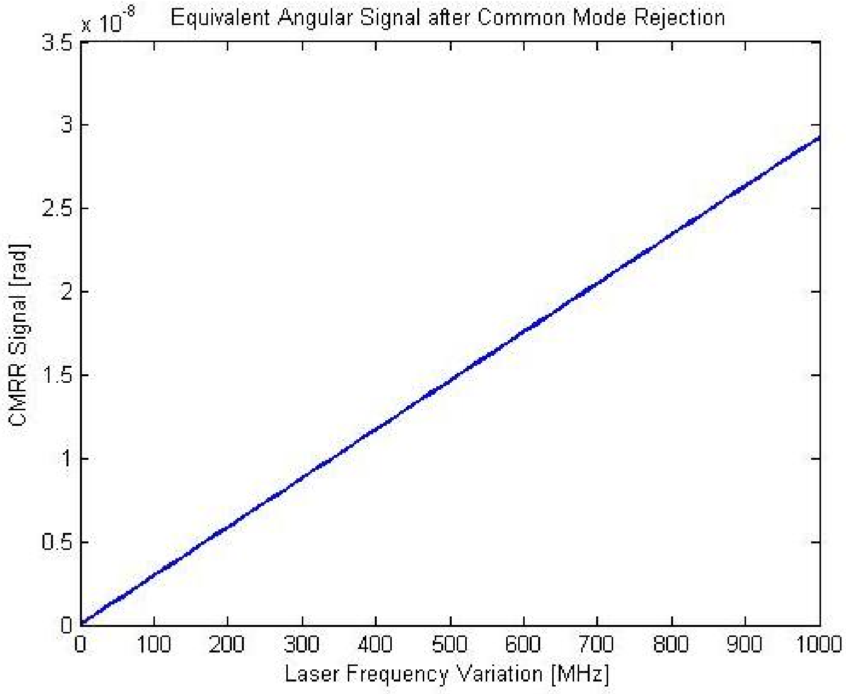
CMRR Loosens Laser Frequency Stability Requirements

Example given: CMRR ~10^3



[kHz]

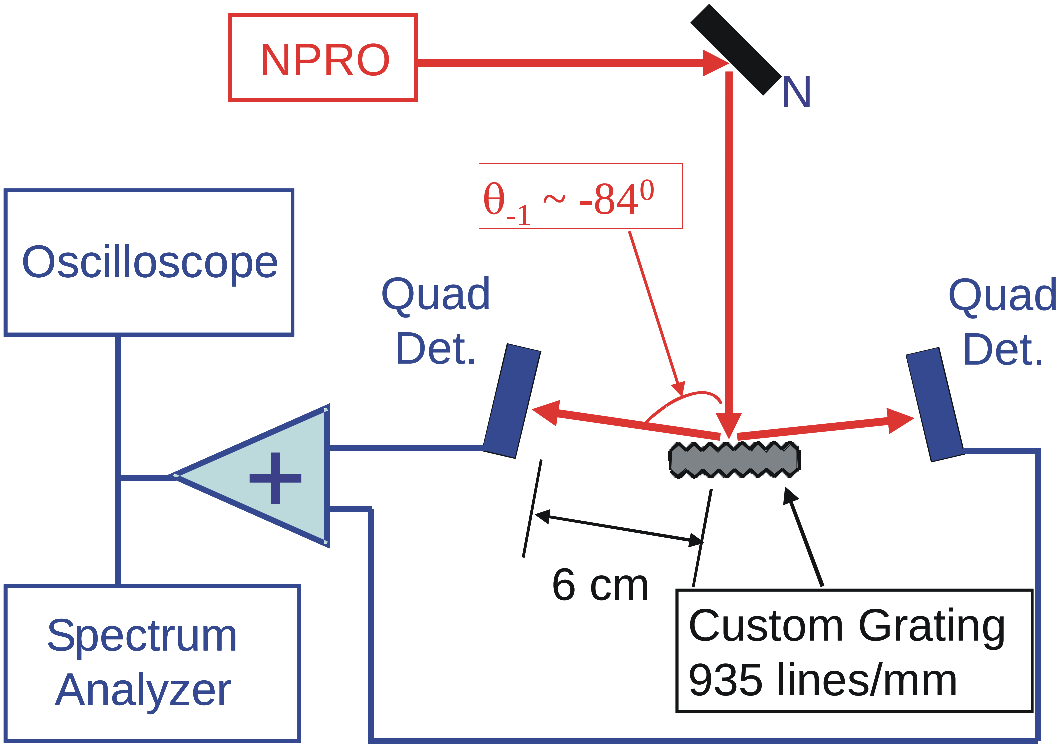
Laser Frequency Requirement:
3 ~ 300 kHz



[MHz]

Laser Frequency Requirement:
3 ~ 300 MHz

Symmetric Grating Angular Senor Experiment



NPRO

N

$\theta_{-1} \sim -84^0$

Oscilloscope

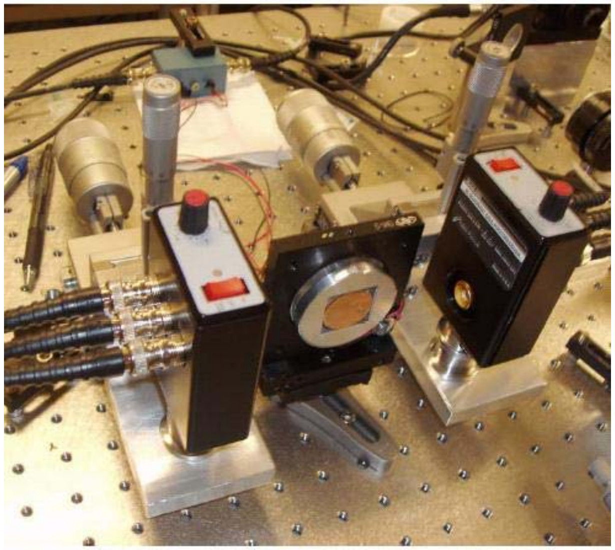
Quad Det.

Quad Det.

6 cm

Custom Grating
935 lines/mm

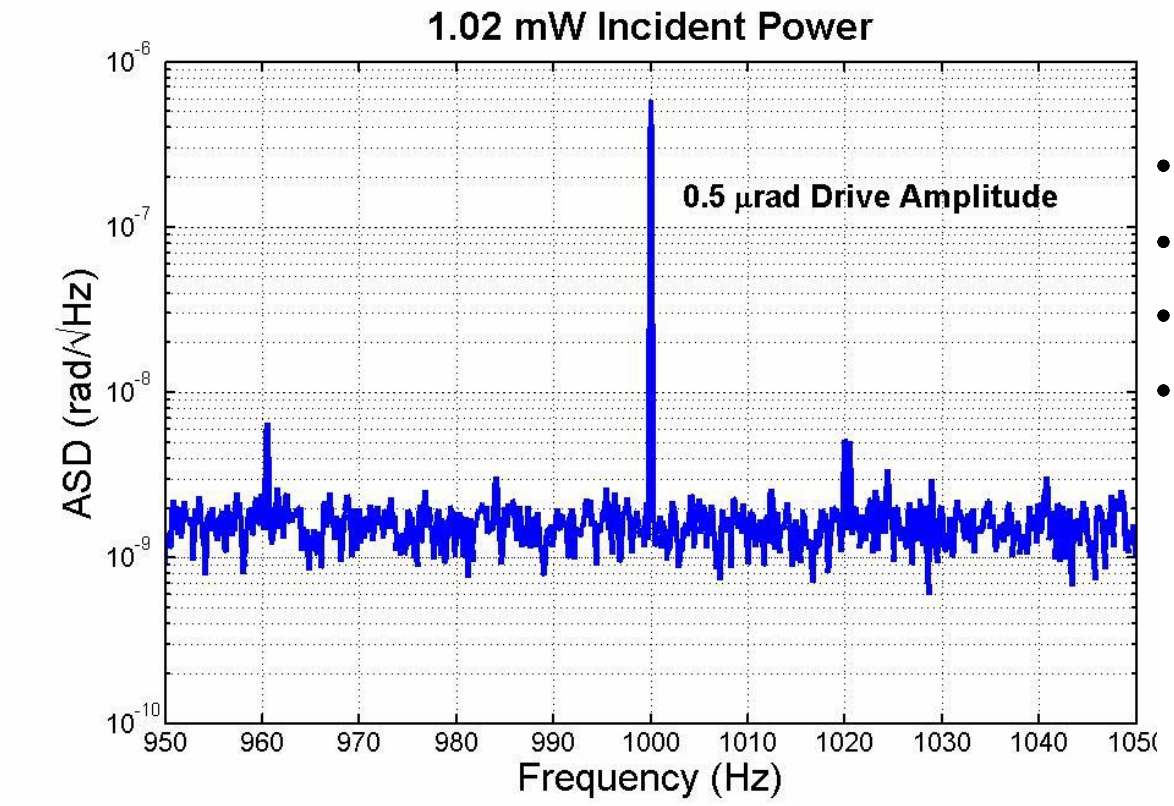
Spectrum Analyzer



Ke-Xun Sun, Patrick Lu, and Robert L. Byer, “A robust, symmetric grating angular sensor”, LISA 6th Symposium, 19-23 June 2006, Goddard Space Flight Center, Greenbelt, MD

Signal Spectrum for 1 mW Incident Power

Noise floor lower than 2 nrad/Hz$^{1/2}$

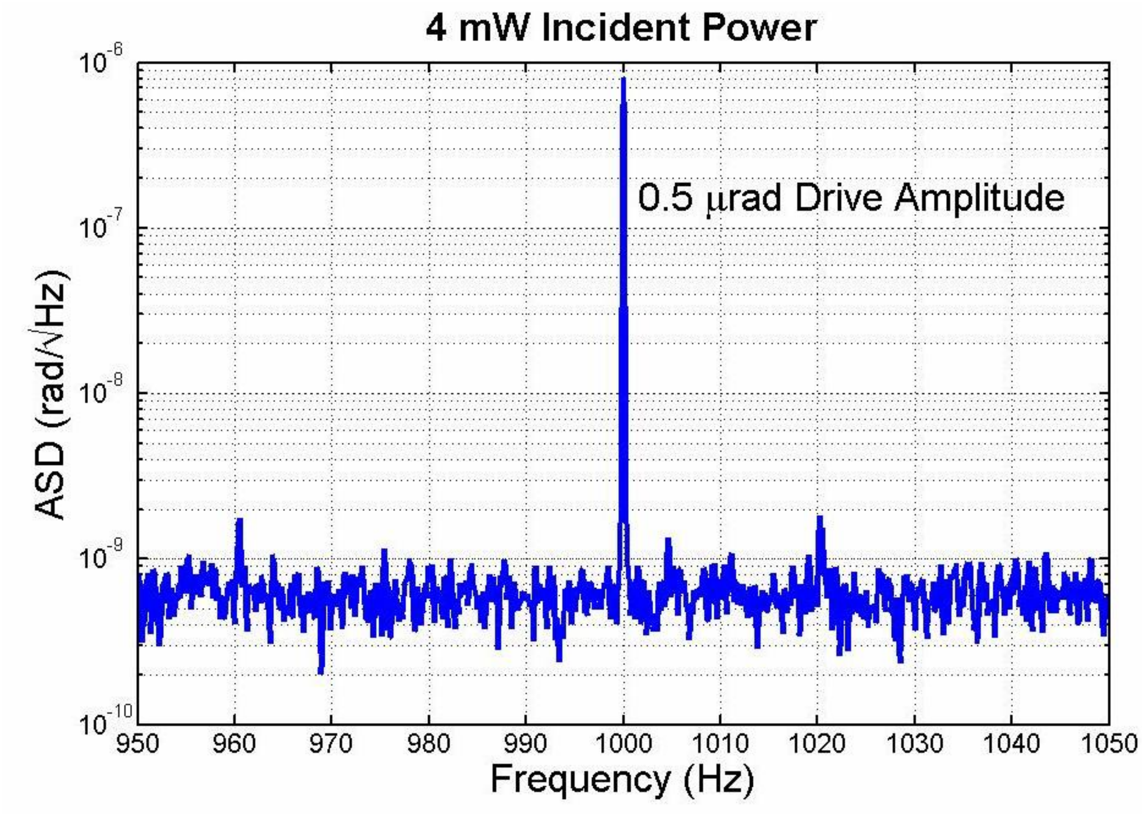


- PZT displacement 10 nm
- Grating rotation 0.5 μrad
- SNR ~50 dB
- Noise floor level

  ~2 nrad/ /Hz$^{1/2}$

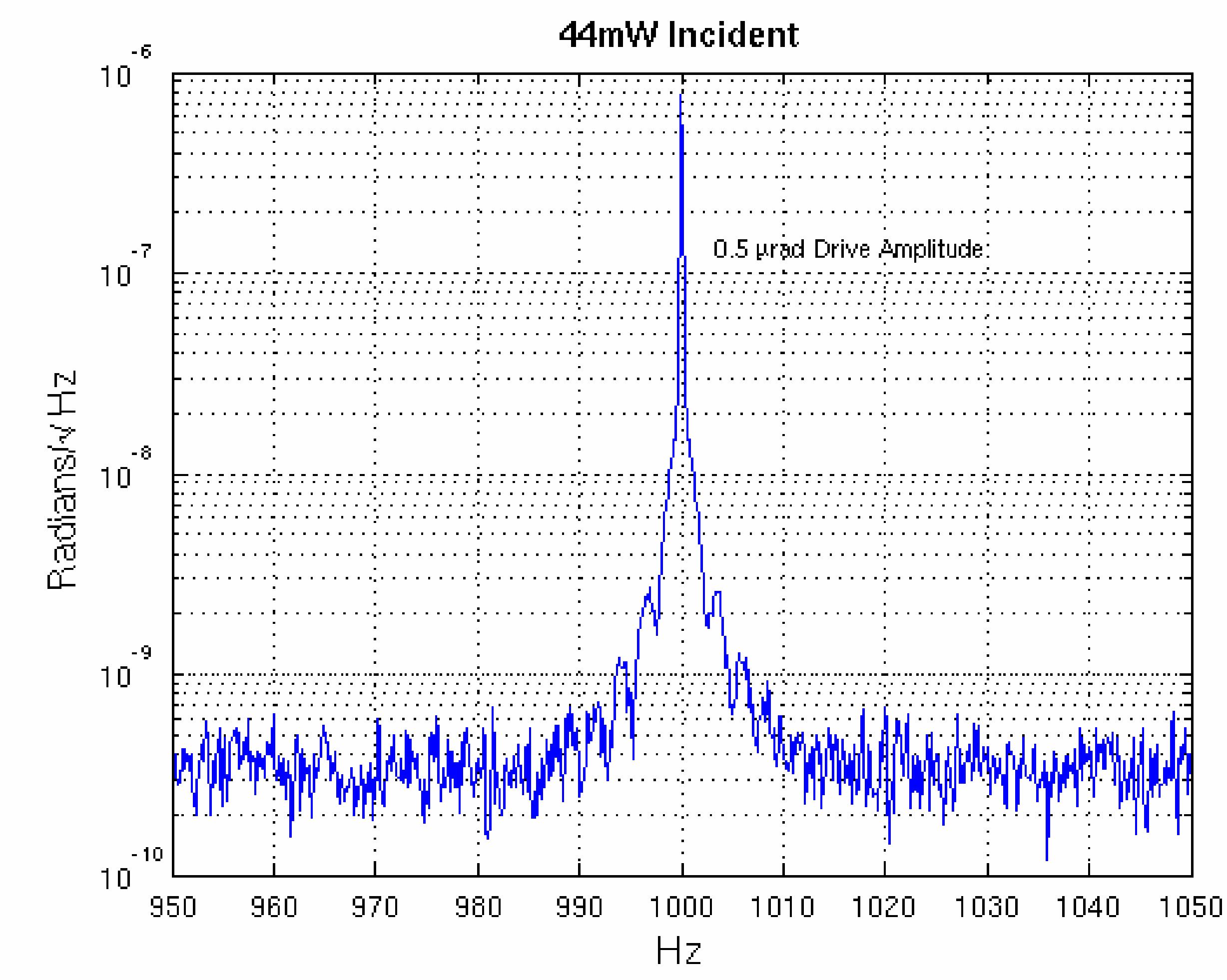
Signal Spectrum for 4 mW Incident Power Signal

Noise floor lower than 1 nrad/Hz$^{1/2}$



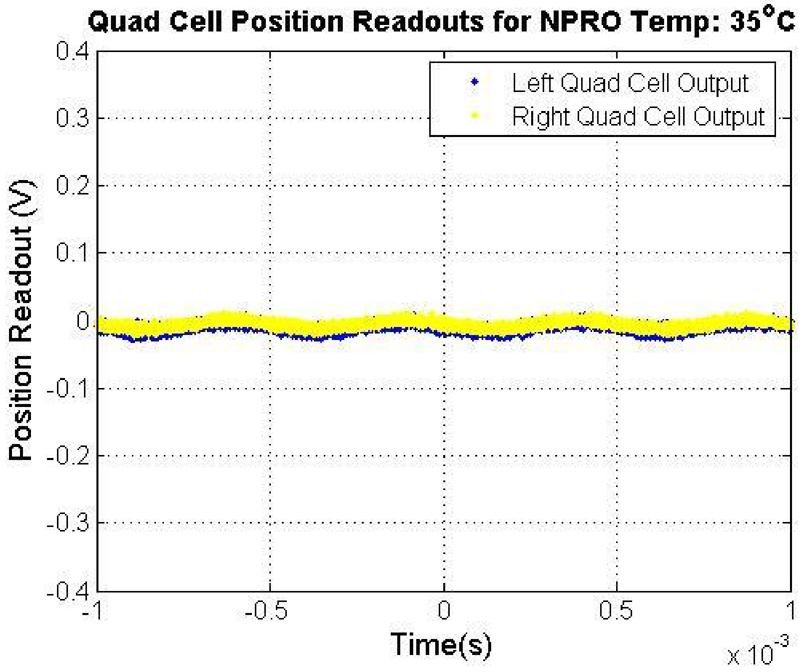
- PZT displacement 10 nm
- Grating rotation 0.5 μrad
- 4 mW input power
- Noise floor level ~1 nrad/ /Hz
- Potential applications:
  - Telescope orientation
  - Fiber collimator orientation
  - Coarse Frequency stabilizatic

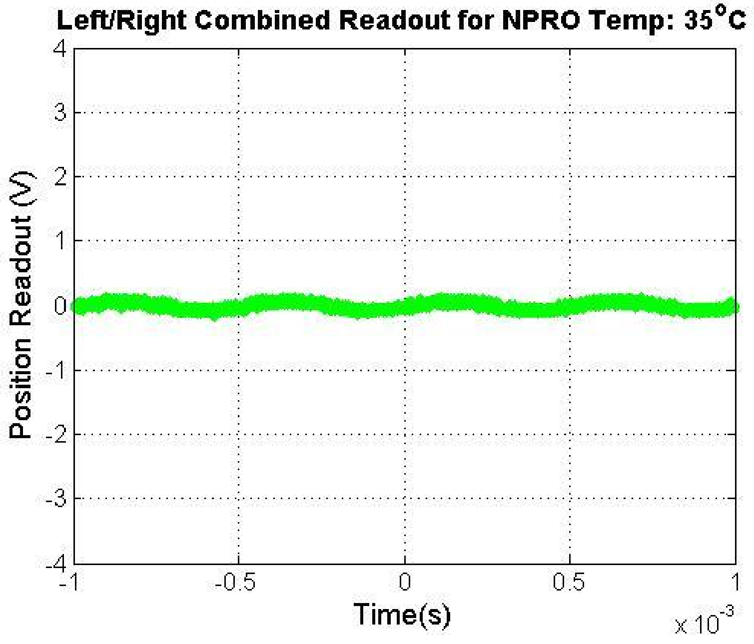
Signal Spectrum for 44 mW Incident Power



- PZT displacement 10 nm
- Grating rotation 0.5 µrad
- 4 mW input power
- Noise floor level ~0.3 nrad/ /$Hz^{1/2}$

Robustness Against Laser Frequency Variations

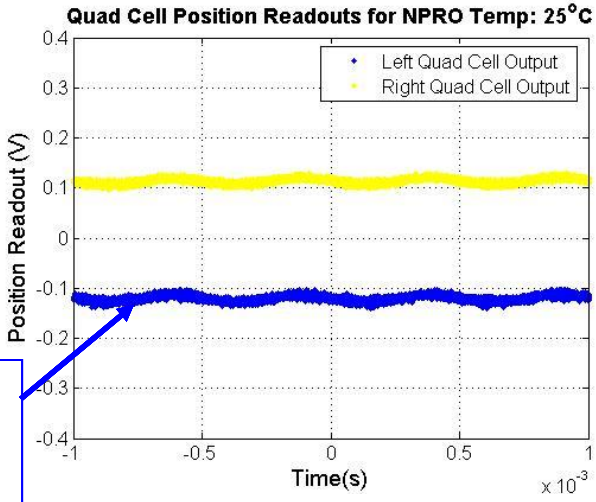


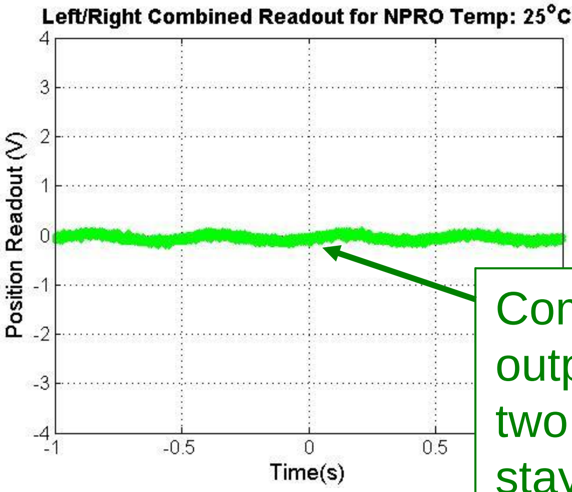


NPRO laser head temperature: 35^0C

Symmetry Enabled Robustness Against Laser Frequency Variations

Laser Freq. @T_{head}=25°C

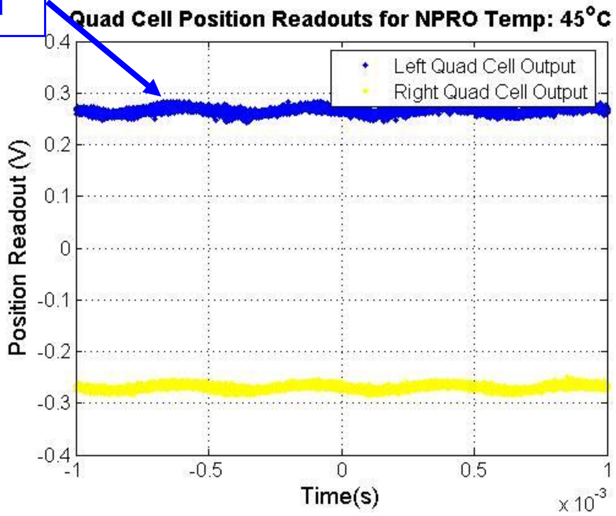

Quad Cell Position Readouts for NPRO Temp: 25°C

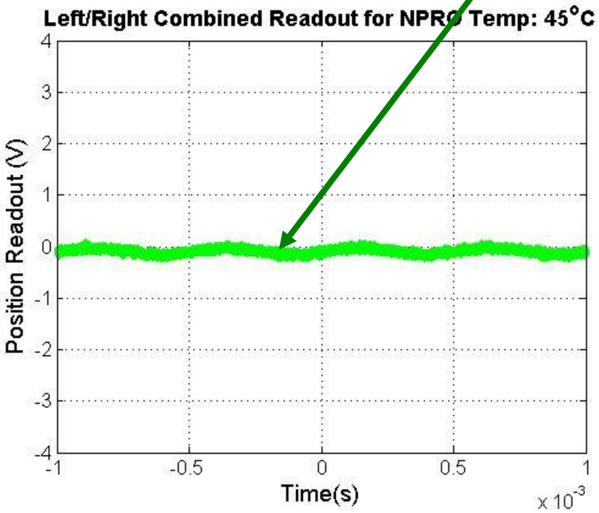

Left/Right Combined Readout for NPRO Temp: 25°C

Combined output from two detectors stay constant

Single quad detector output moved

Laser Freq. @T_{head}=45°C

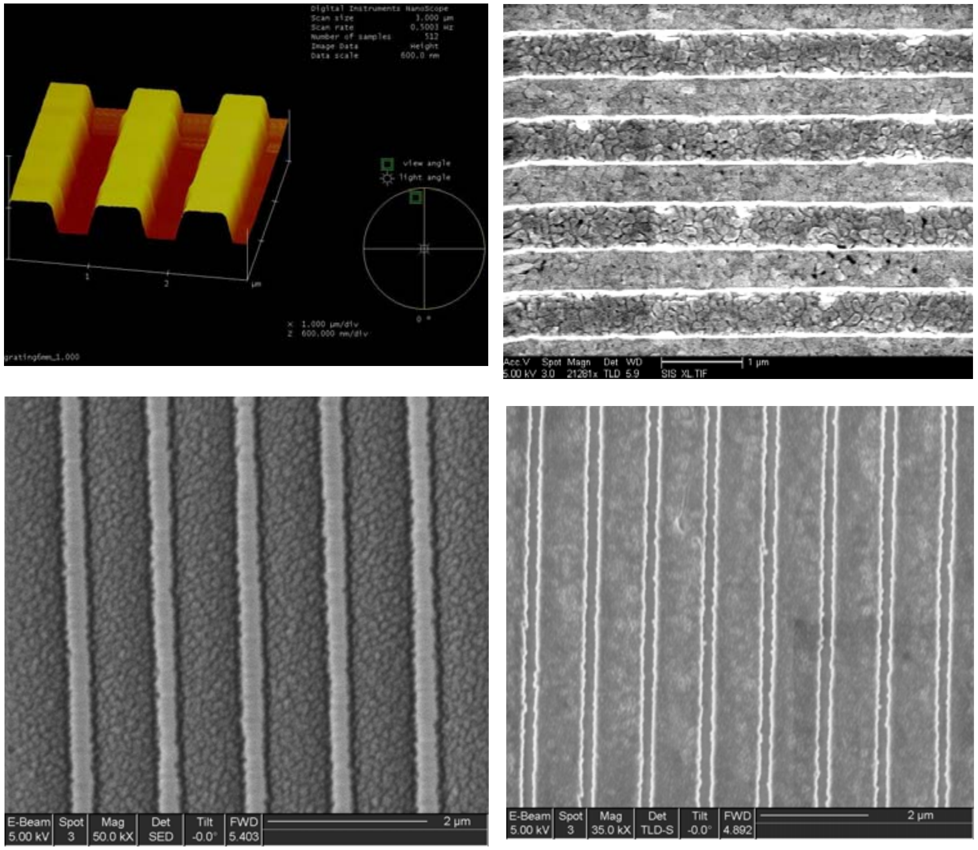

Quad Cell Position Readouts for NPRO Temp: 45°C


Left/Right Combined Readout for NPRO Temp: 45°C

NPRO laser head temperature: 25^0C & 45^0C

Improvements of Grating Quality

- Transfer-imprinting of gold gratings
  - This is performed by pressing a dielectric grating into a gold surface with force sufficient to exceed the yield stress of gold
  - Centimeter-sized dielectric gratings were fabricated with e-beam lithography on quartz wafers.
  - Gold gratings had 933 lines/mm and 300nm of depth.
  - Various duty cycles have been demonstrated.
  - 275nm depth 50% duty cycle gold gratings have been measured to have 26% diffraction efficiency in the +/-1 orders and 36% efficiency in the 0th order.

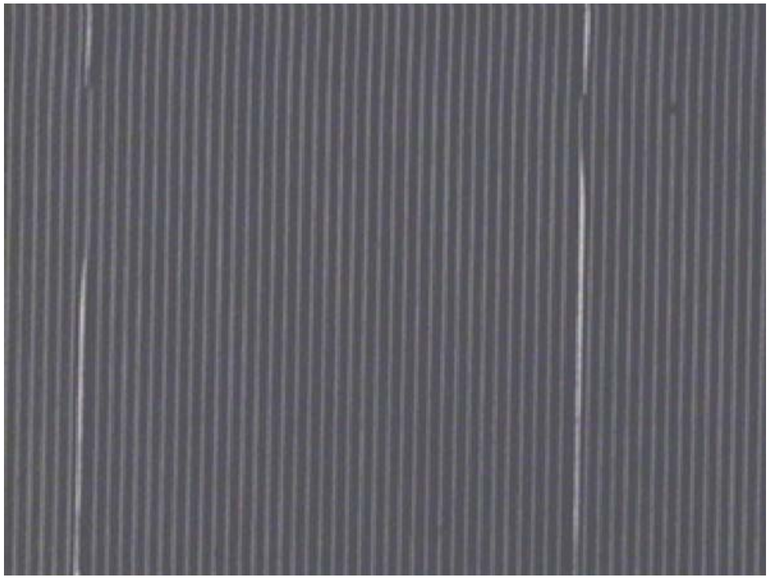


Patrick Lu, Ke-Xun Sun, and Robert L. Byer, “Methods of Fabricating Grating Patterns on Dielectric and Metal Surfaces”, LISA 6th Symposium, 19-23 June 2006, Goddard Space Flight Center, Greenbelt, MD

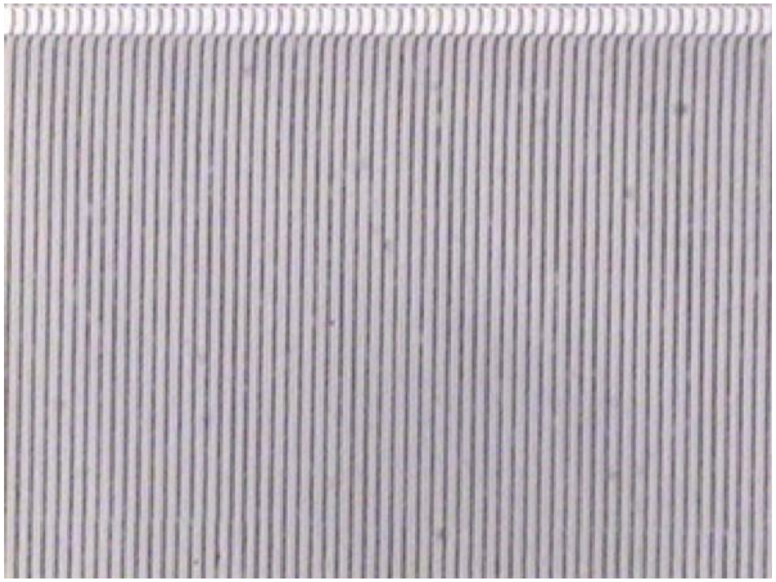
Grating Fabrication Improvements

1. Electron-beam lithographic techniques for dielectric gratings
   - More masking in all steps
2. Trans-Imprinting for metallic gratings
   - pressure optimization
3. Focused Ion Beam
   - Beam current optimization
   - Focusing optimization
4. Ion etcher (Collaboration with LLNL)

Grating Duty Cycle Variation



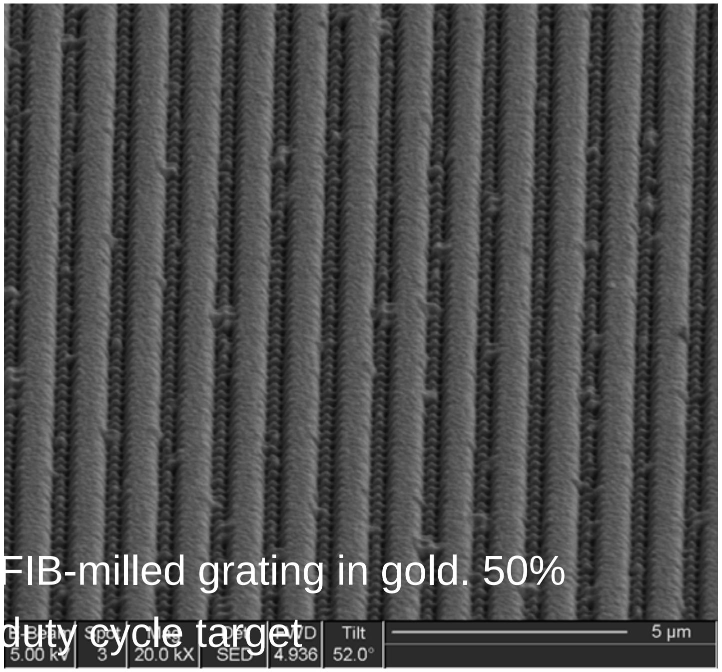
Chrome etch mask
25% duty cycle.



Chrome etch mask
75% duty cycle.

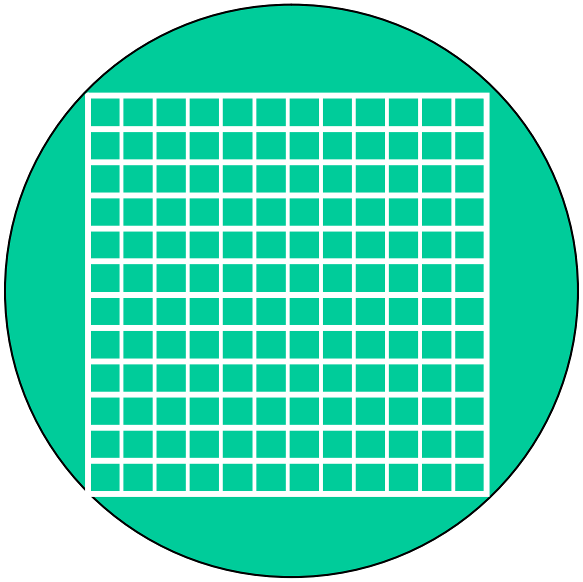
Grating Fabrication for Grating Angular Sensor

- Direct ion milling of gold gratings
  - 1 mm gratings with 50% duty cycle and 300nm depth have been fabricated.
  - Performed using an FEI Focused Ion Beam machine
  - Efficiency of +/-1 order: >20%
  - Studying the “side lobes”



FIB-milled grating in gold. 50% duty cycle target

Gratings Can Be Cost Effective



- 2 mm or 3 mm square grating is big enough for

- Smaller gratings can cut from a large wafer
- 100s gratings made at once time
- 10s dollars per grating

Conclusion

- Symmetric grating angular sensor sensitivity beats 1 nrad/Hz$^{1/2}$
- Symmetric grating angular sensor with proper electronics chain is more robust against laser frequency noises
- In-house grating fabrication techniques allow grating elements to be produced cost effectively
- Future tasks
  - Electronics for higher sensitivity
  - Environmental control for lower frequencies

Acknowledgements

- Support for this project comes from
  - NSF LIGO for gravitational wave detection
  - LLNL for supporting high power dielectric grating development for Stanford LIGO program
  - JPL DRDF for precision angular sensing for LISA proof mass sensing