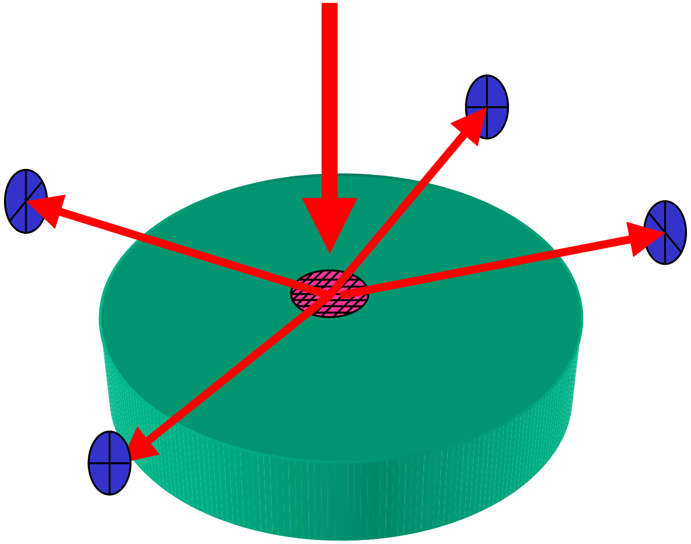
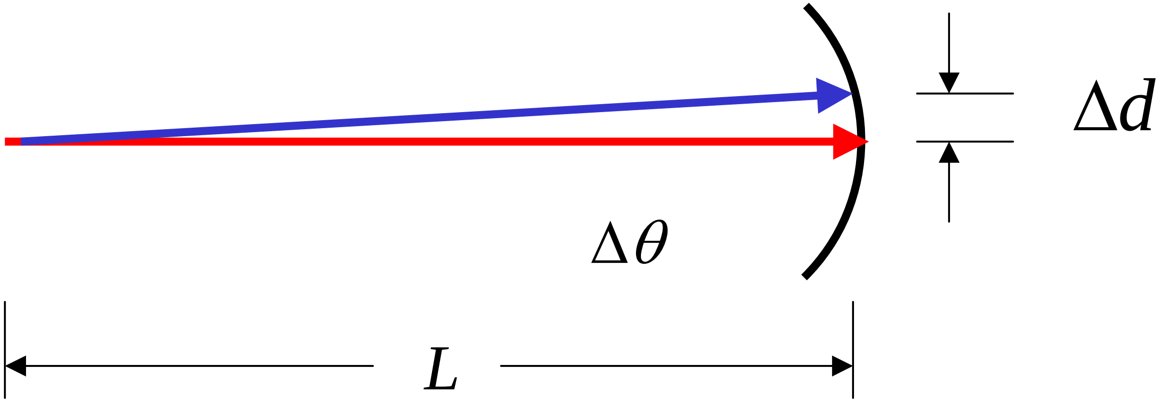
Compact, High Precision Grating Angular Sensor for LIGO Interferometer Control



Ke-Xun Sun and Robert Byer
Stanford University

LIGO Science Collaboration (LSC) Meeting
Technical Plenary Presentation
LIGO Hanford Observatory
16 August 2005

Angular Sensing Requirements for LIGO



- Beam center offset requirement for reduction of coupling
  - LIGO: 1 cm
  - Advanced LIGO: 1 mm
- LIGO beam pointing angular sensing resolution

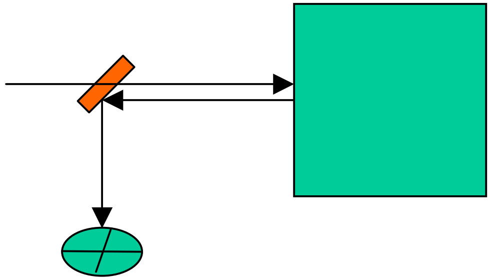
$$\Delta\theta_{\mathrm{LIGO}} \le \Delta d / L = 10^{-2} / 4\times10^{3} = 2.5\ \mu\mathrm{rad}$$

$$\Delta\theta_{\mathrm{Adv.LIGO}} \le 0.1\times\Delta\theta_{\mathrm{LIGO}} = 0.25\ \mu\mathrm{rad}$$

Optical Lever Angular Sensing Schemes

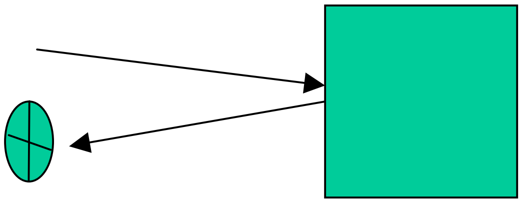
- Direct optical reflection, beam folding by unstable optics

$$\Delta y \approx L'\Delta\theta$$



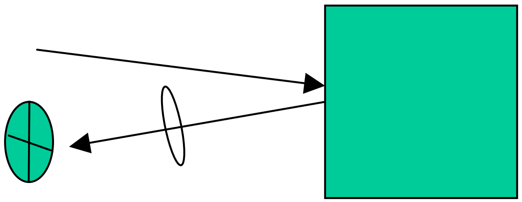
- Direct optical reflection : no optics in line but still limited by length

$$\Delta y \approx L\Delta\theta$$



- Telescope and focusing optics assisted optical lever: Could be more sensitive but complex, unstable optics in line

$$\Delta d \approx L_{\mathrm{FL}}\Delta\theta$$



40 m Interferometer Optical Lever for LIGO Angular Sensing and Control

Optical lever

- Installed widely for alignment for many optics
- Sensitivity level requires long working distance
- Telescope used to magnify the angle and reduce the working distance
  - Telescope induced beam wobbling?
  - Any way to lower the cost?

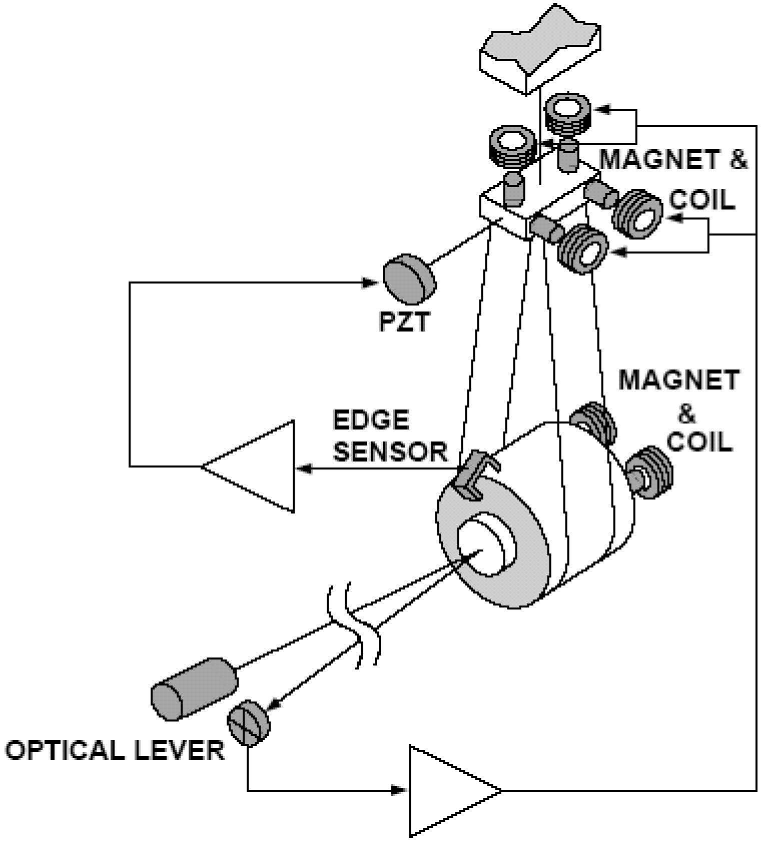
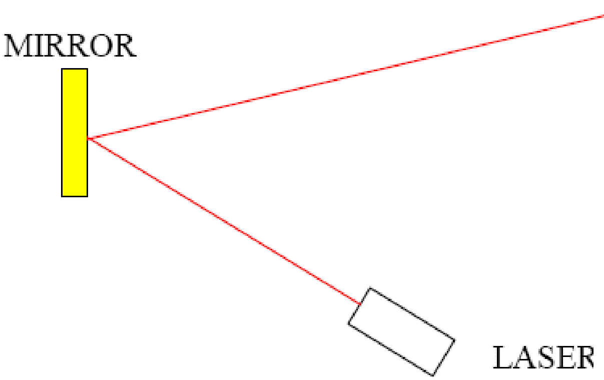
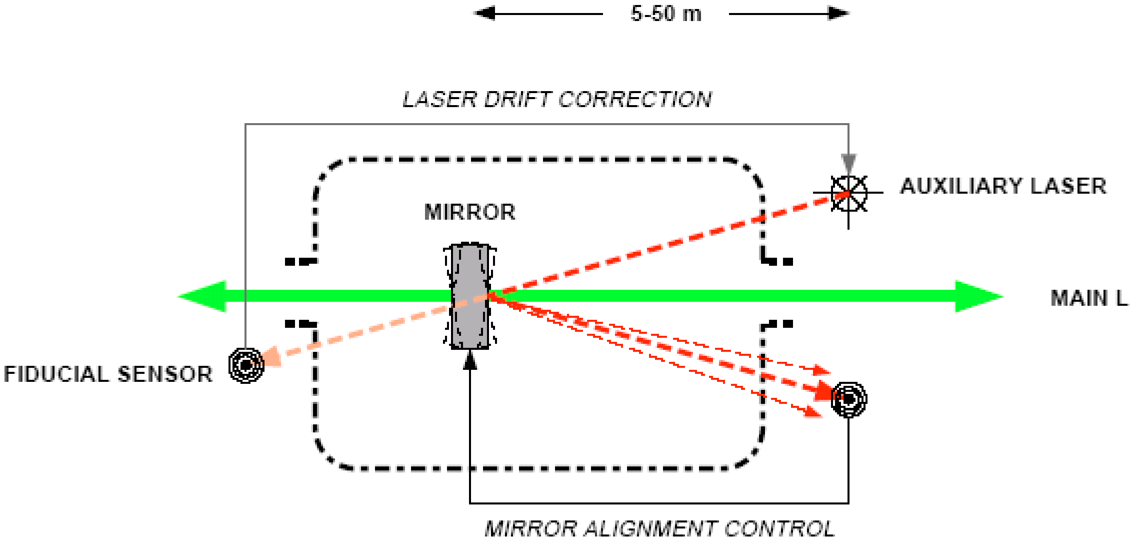


Figure 15: Schematic of a suspended test mass and its control hardware (40m interferometer design)

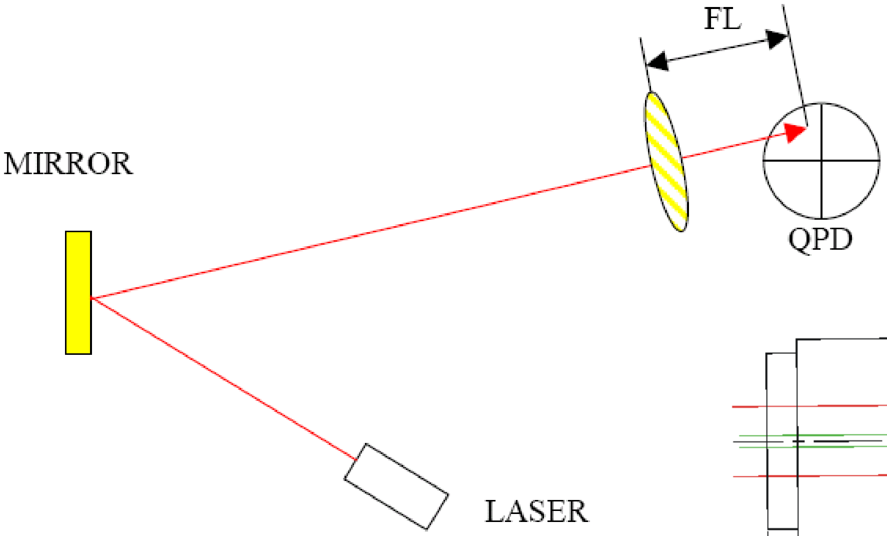
Angular Sensing Optical Lever for LIGO Interferometer Control

Installed widely for alignment for many optics



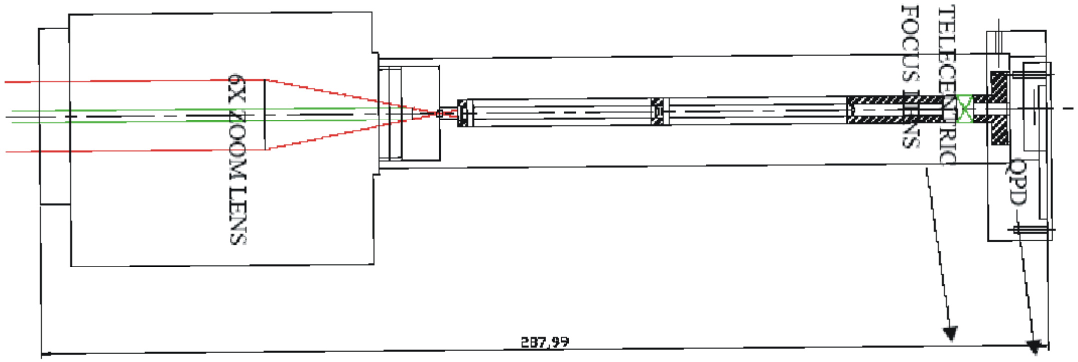


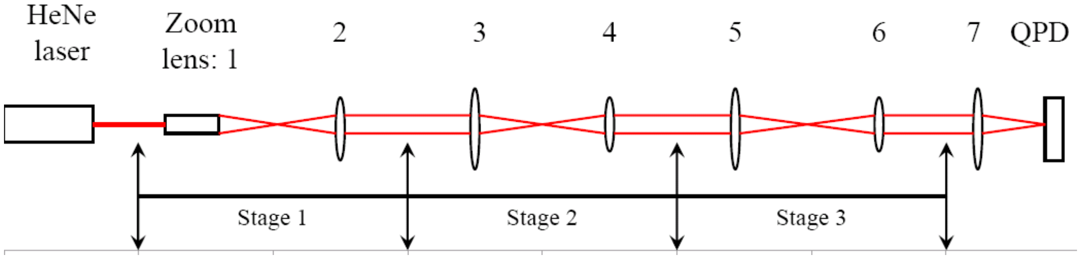
Telescope and Focusing Lens Assisted Optical Lever



D. Reese McKay, Dennis Ugolini
Trinity University

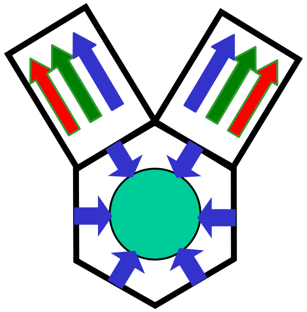
Mike Smith
California Institute of Technology





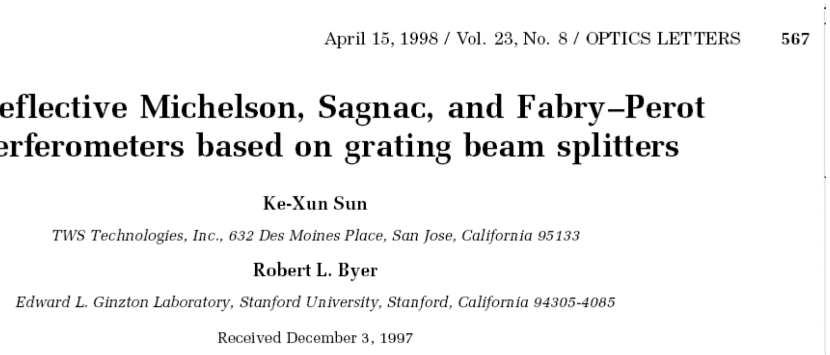
Previous Interferometry Work

- Zero-area Sagnac experiment and analysis (1994~1995)
  - Experiment & Analysis of Sagnac response to gravitational wave
  - Compare to LISA data analysis baseline (X, X_1)
  - Polarization multiplexed, co-path local oscillator with post modulation
- Grating interferometers (1996)
  - All-reflective Michelson, Sagnac, Fabry-Perot interferometers
- LISA stand-alone GRS and interferometer architecture (2003)
  - Single proof mass with optical sensing (adopted by BBO in 2004)
  - Remote laser does not illuminate proof mass, direct precision measurements without routing (adopted by LISA in 2005)



- Grating sensors for LISA/ST7 (2004)
  - Angular sensor (Funded by JPL DRDF program)
  - Integrated displacement and angular sensor
- LED UV source for LISA proof mass charge management (2005)
  - Deep UV LED source to replace mercury lamp (May fly in ST7/LISA)
  - AC charge management to reduce disturbance

Two-Port Grating Interferometry



April 15, 1998 / Vol. 23, No. 8 / OPTICS LETTERS 567

All-reflective Michelson, Sagnac, and Fabry–Perot interferometers based on grating beam splitters

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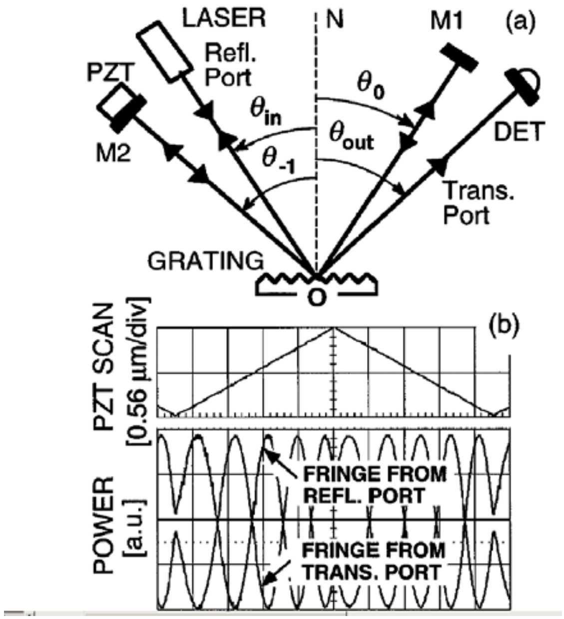
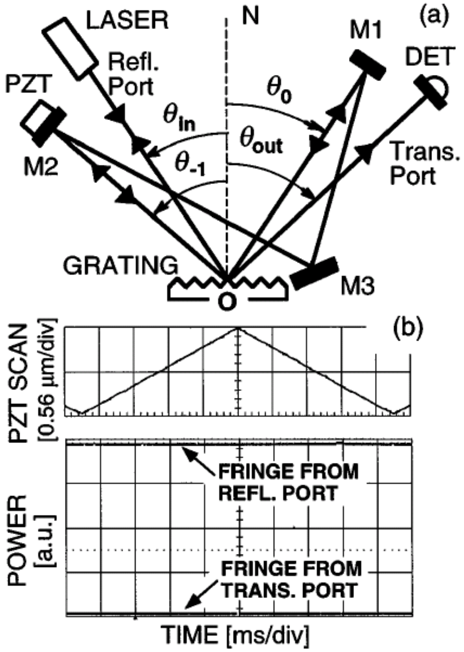
TWS Technologies, Inc., 632 Des Moines Place, San Jose, California 95133

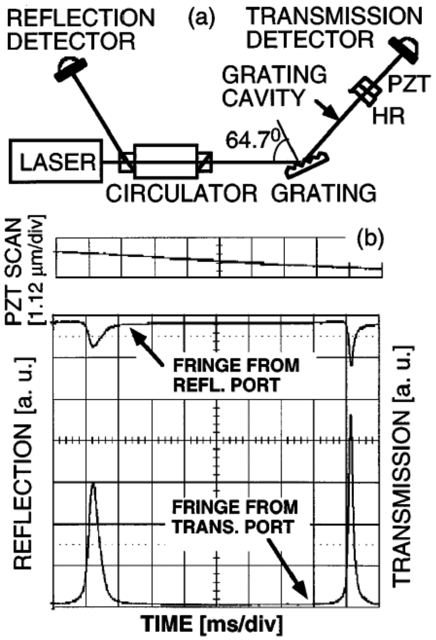
Robert L. Byer

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

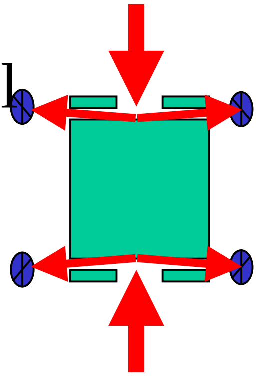
Received December 3, 1997







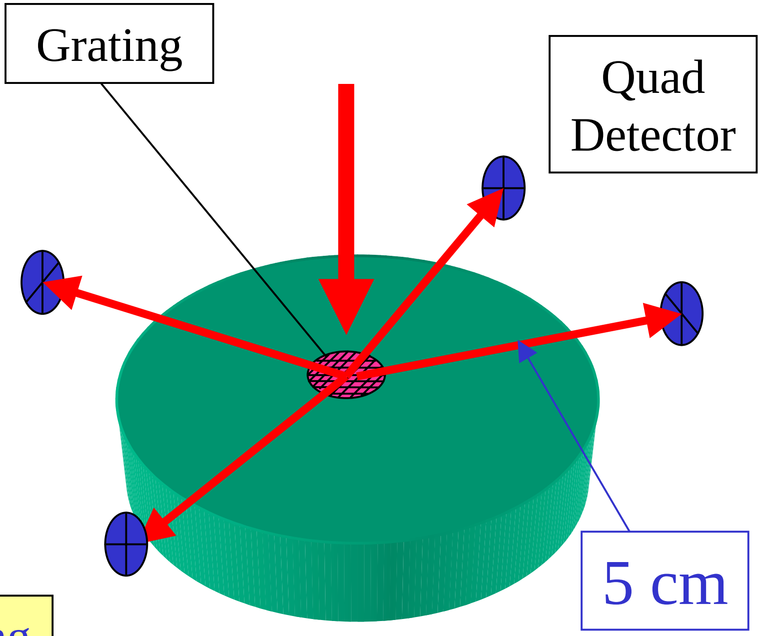
Grating Angular Sensor



No Transmissive Optics Components: Enhanced Thermal Stability

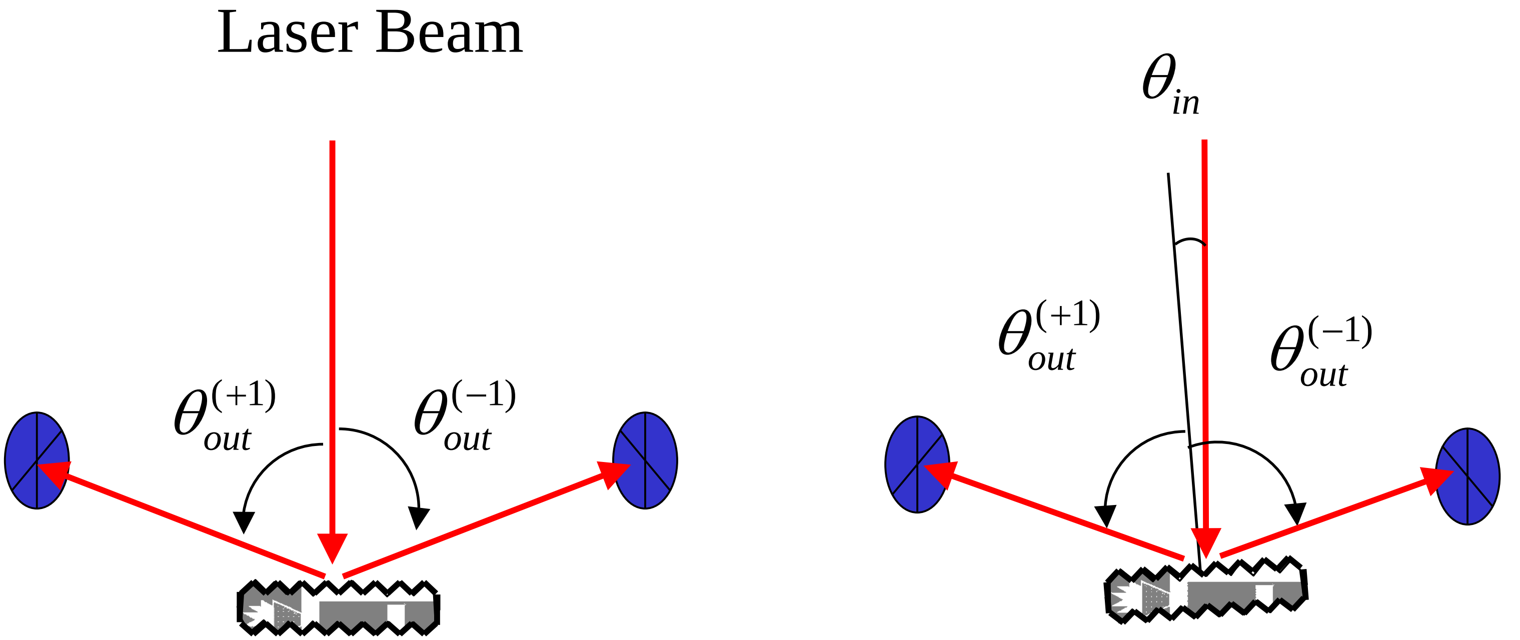
No Additional Optics: Enhanced Signal Integrity

- 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

Grating Based Angular Sensor
Diffractive Angular Interferometry



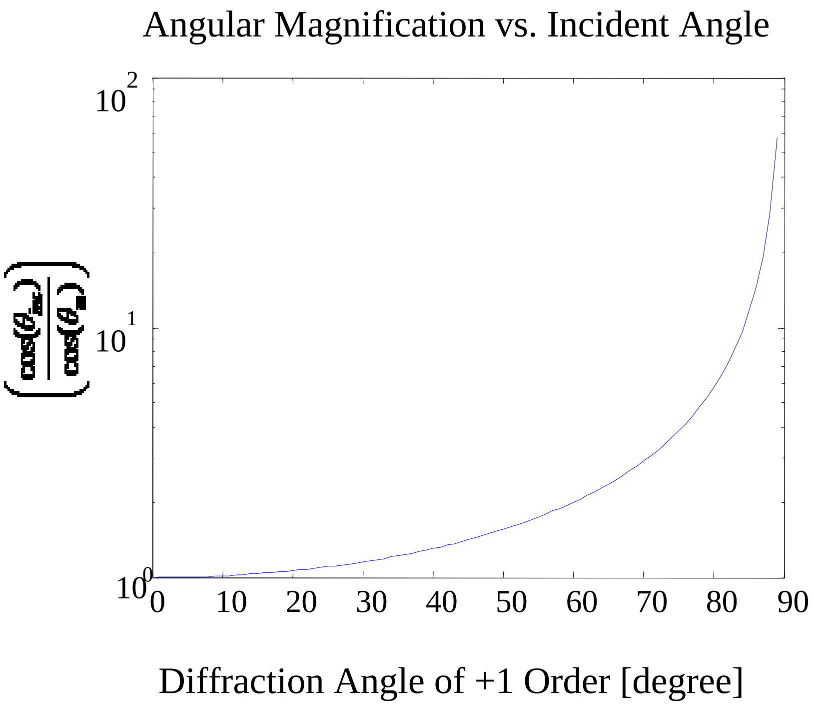
$$d\left(\sin\theta_m - \sin\theta_{in}\right) = m\lambda$$

Grating Angle Amplification

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

$$\cos(\theta_m)\Delta\theta_m = \cos(\theta_{inc})\Delta\theta_{in}$$

$$\Delta\theta_m = \left(\frac{\cos(\theta_{inc})}{\cos(\theta_m)}\right)\Delta\theta_{in}$$



Grating angle magnification significant at grazing angle output

Energy Density Enhancement by Projection

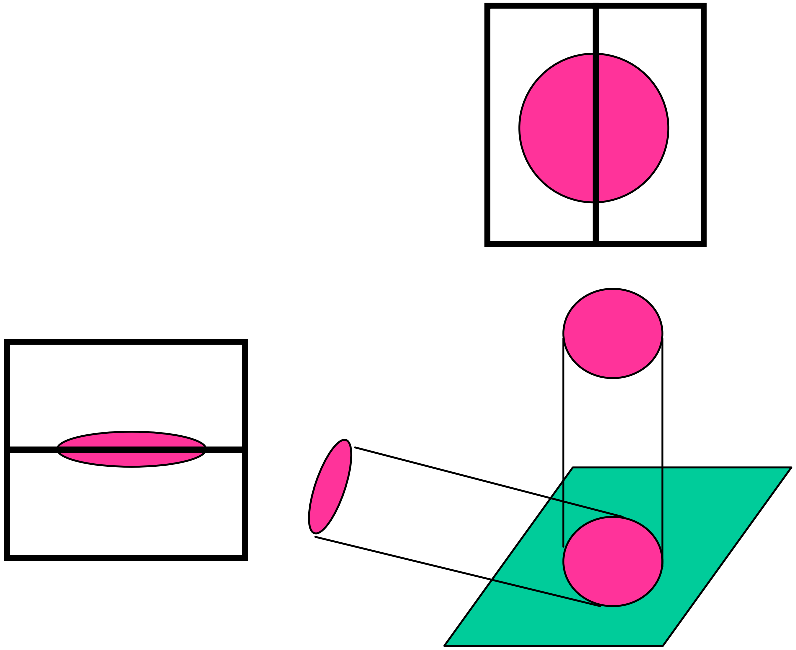
Beam compression in relevant dimension without using a focusing lens

Beam projection minimization:

$$A_m = \left(\frac{\cos(\theta_m)}{\cos(\theta_{in})}\right) A_{in}$$

Laser beam energy density enhancement:

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

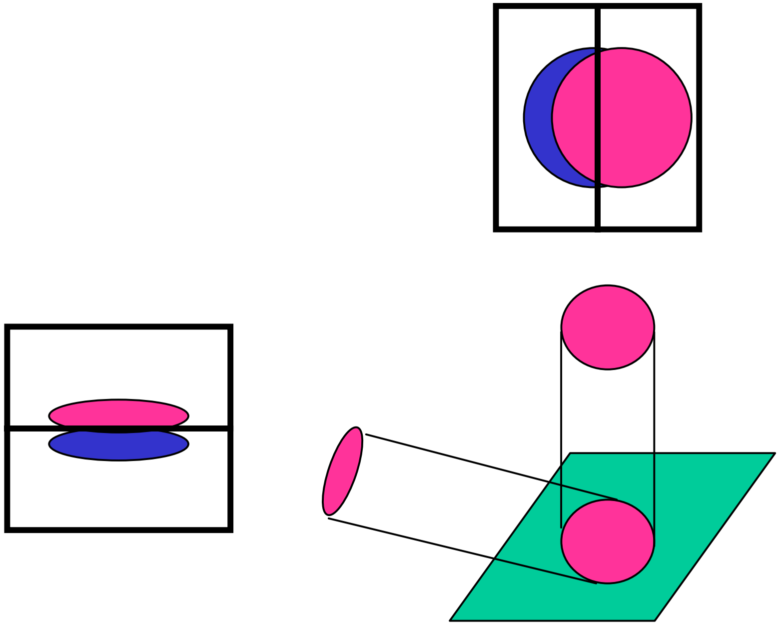


Dynamic Differential Photo Current Enhancement in Divided Photodiodes

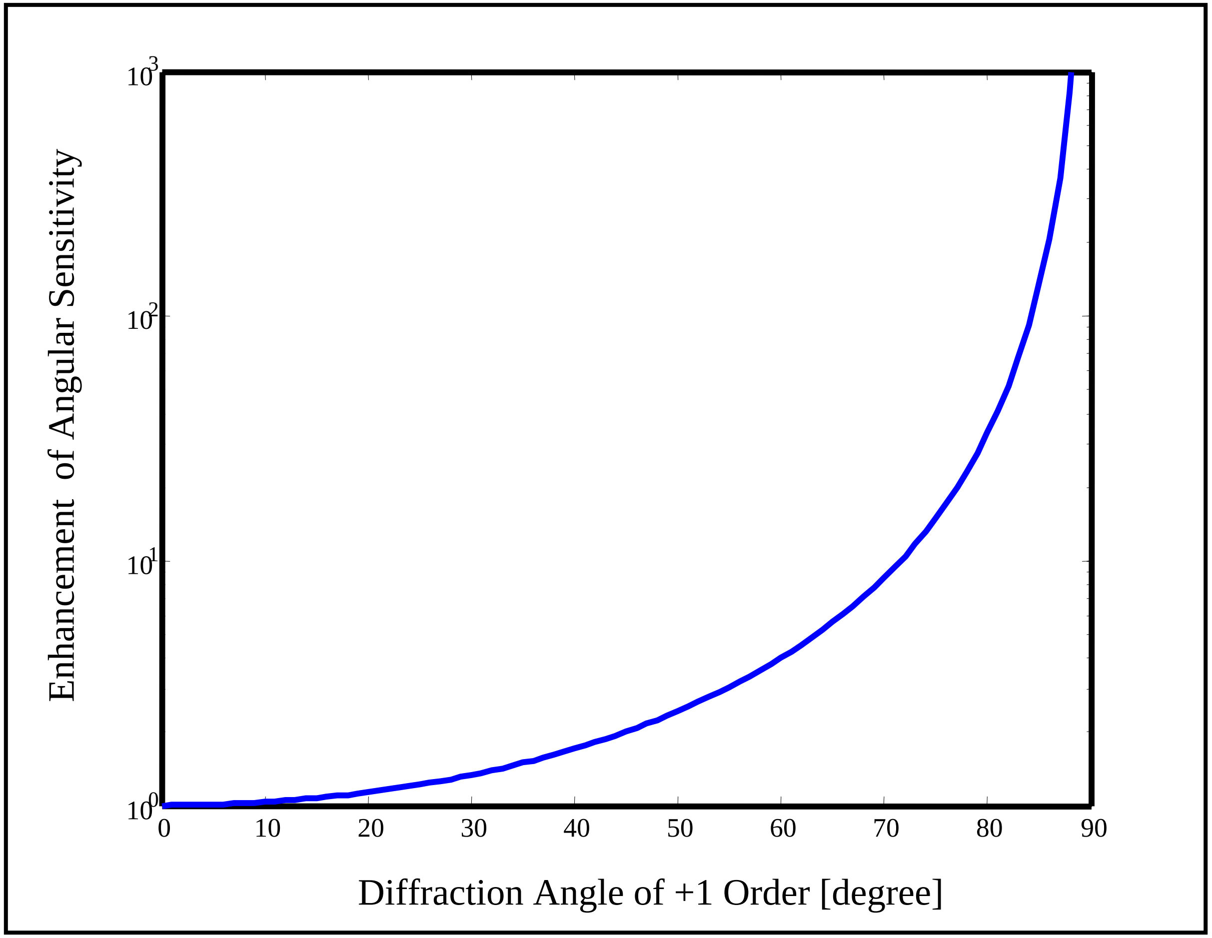
$$\Delta I = I_u - I_d \qquad I_{tot} = I_u + I_d$$

Enhancement due to
1. Angular magnification
2. Projection area minimization

$$\Delta I_m = K''\left(\frac{\cos(\theta_{inc})}{\cos(\theta_m)}\right)^2 \Delta I_{direct}$$



Overall Enhancement of Angular Sensitivity



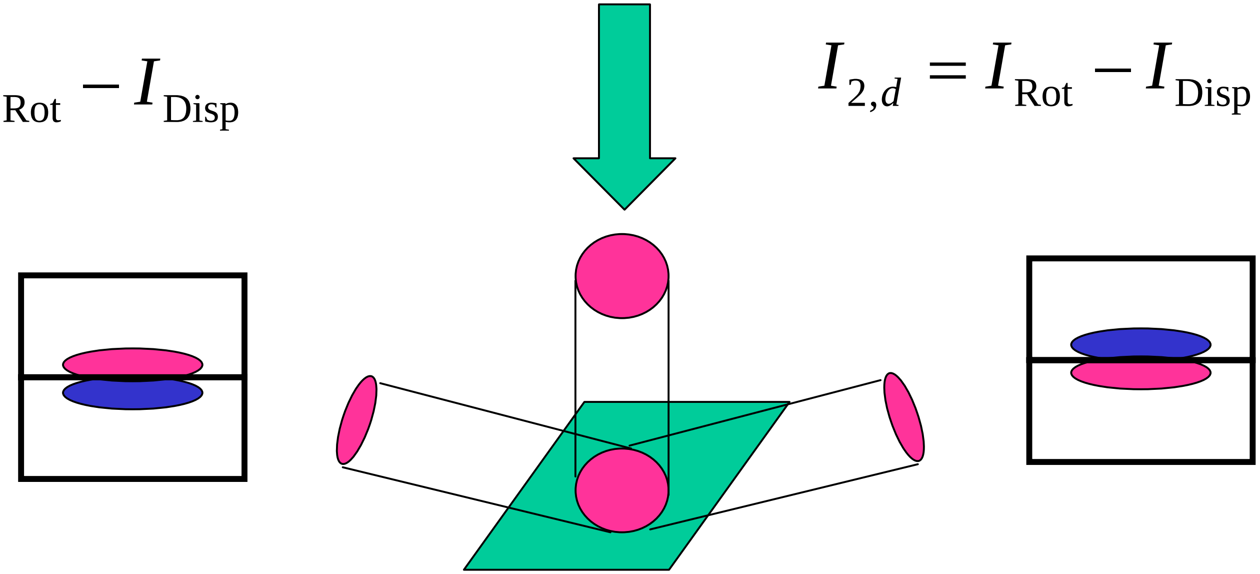
Signal Processing to Cancel Displacement Component and Extract Pure Rotation Information

$$I_{1,u} = I_{\text{Rot}} + I_{\text{Disp}}$$

$$I_{1,d} = -I_{\text{Rot}} - I_{\text{Disp}}$$

$$I_{2,u} = -I_{\text{Rot}} + I_{\text{Disp}}$$

$$I_{2,d} = I_{\text{Rot}} - I_{\text{Disp}}$$

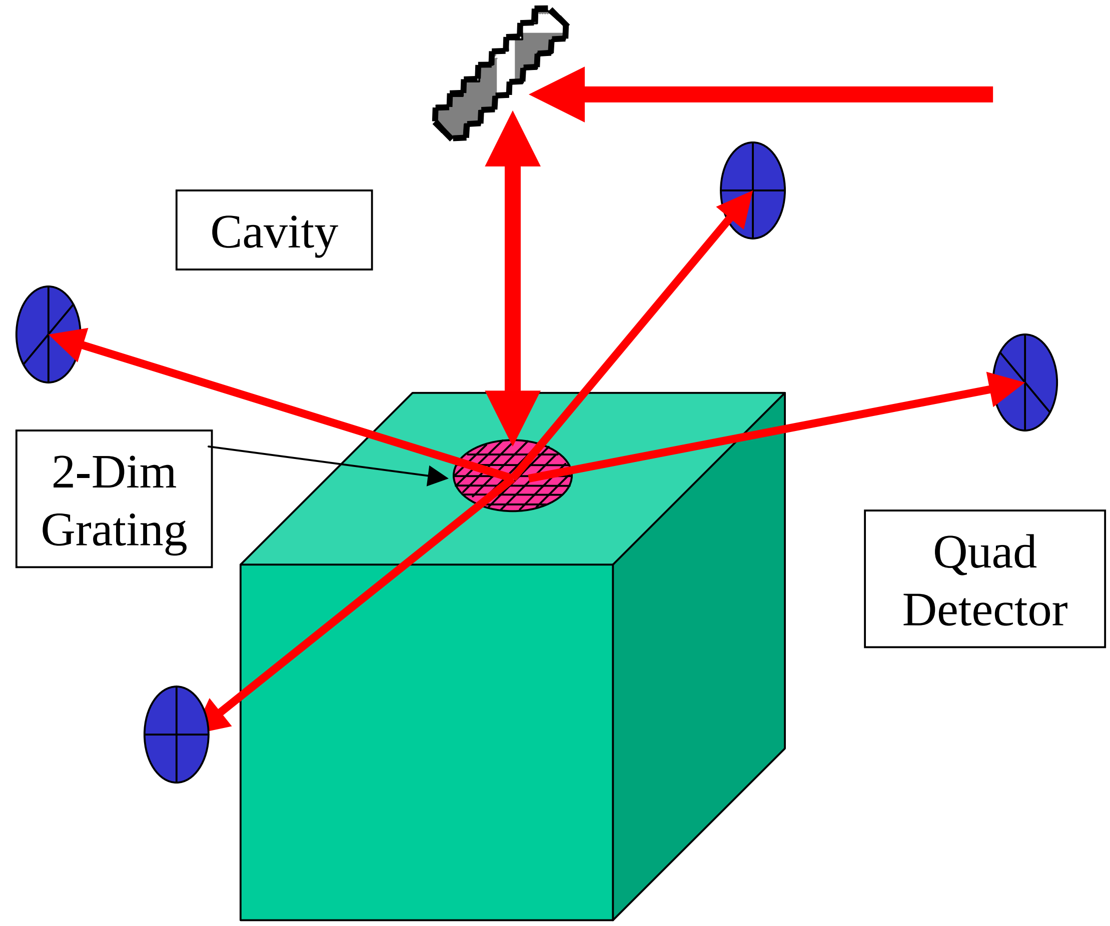


$$\Delta I_1 = I_{1,u} - I_{1,d}$$

$$\Delta I_2 = I_{2,u} - I_{2,d}$$

$$\Delta(\Delta I) = \Delta I_1 - \Delta I_2 = 4I_{\text{ROT}}$$

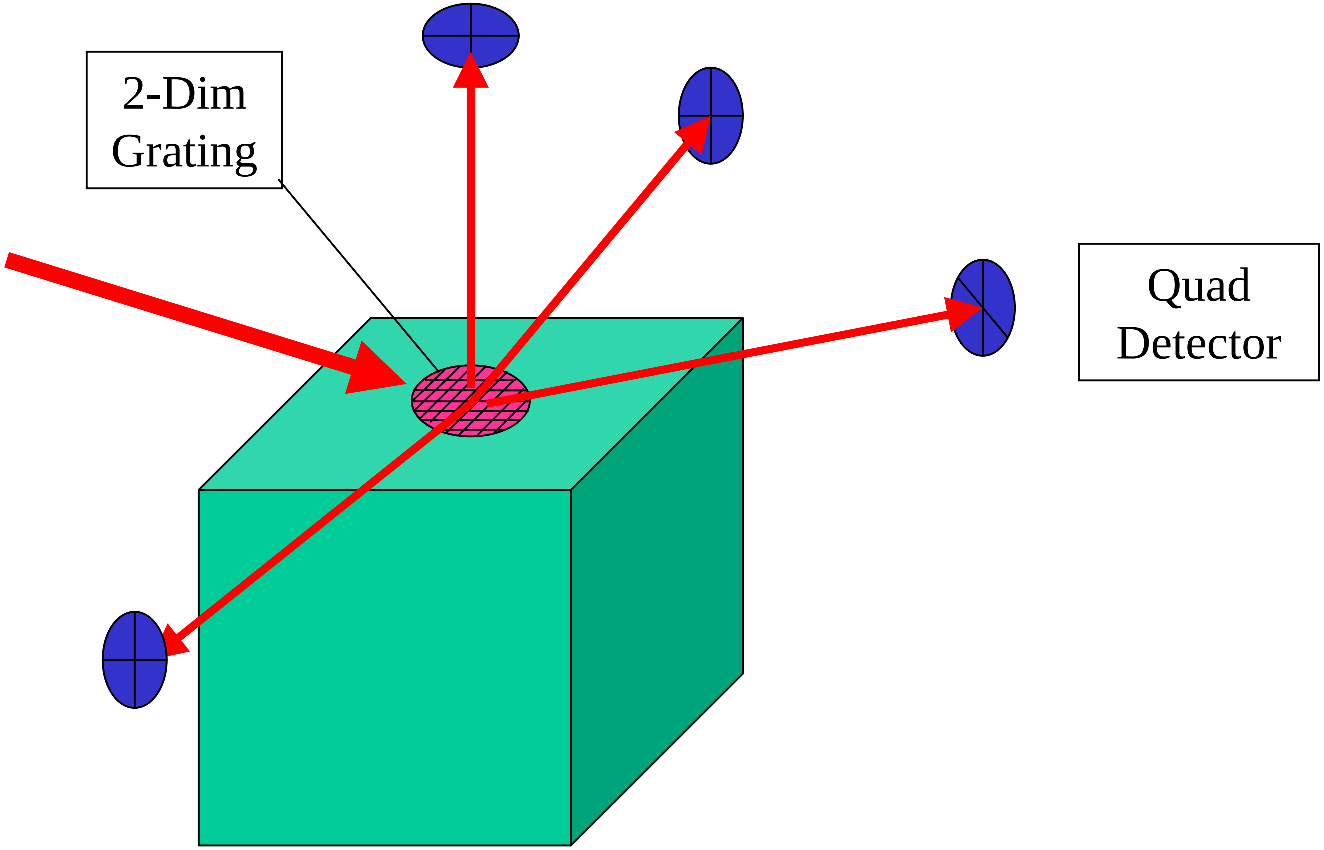
Integrated Displacement and Angular Diffractive Optics Sensor


Cavity

2-Dim Grating

Quad Detector

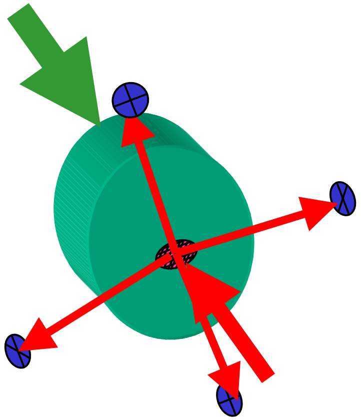
Angular Sensor Using Diffractive Optics Tilted Incident Beam: Expanded Dynamic Range



2-Dim Grating

Quad Detector

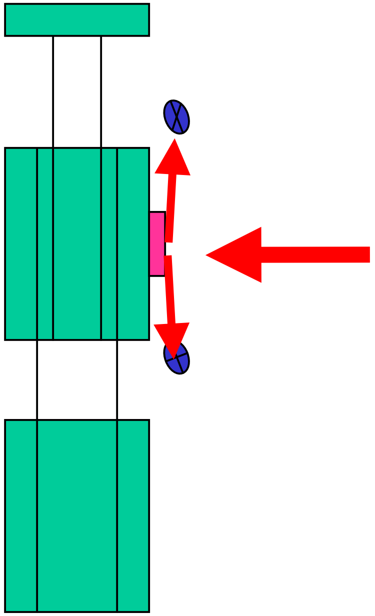
Possible LIGO Installation Options (I)



Back of the high reflectors

(Including AR side of partial reflector)

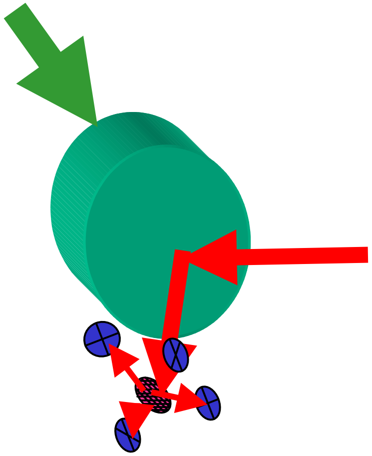
Additional rotational sensitivity

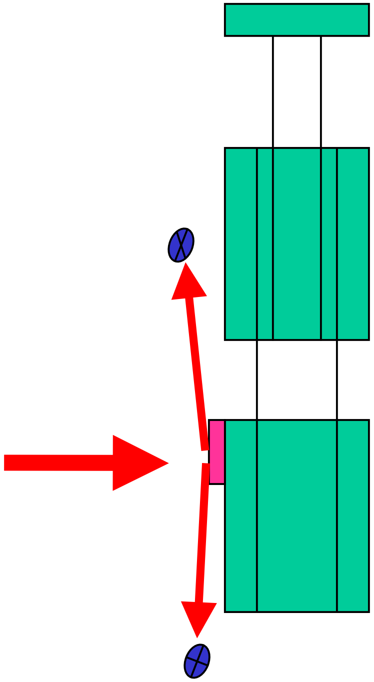


Intermediate test mass

Or suspension point interferometer

Possible LIGO Installations Options(II)
Grating as a Rotation Analyzer





Grating
(Including AR side of partial reflector)
Additional rotational sensitivity

Somewhere in the main beam?
Needs only 100 μW

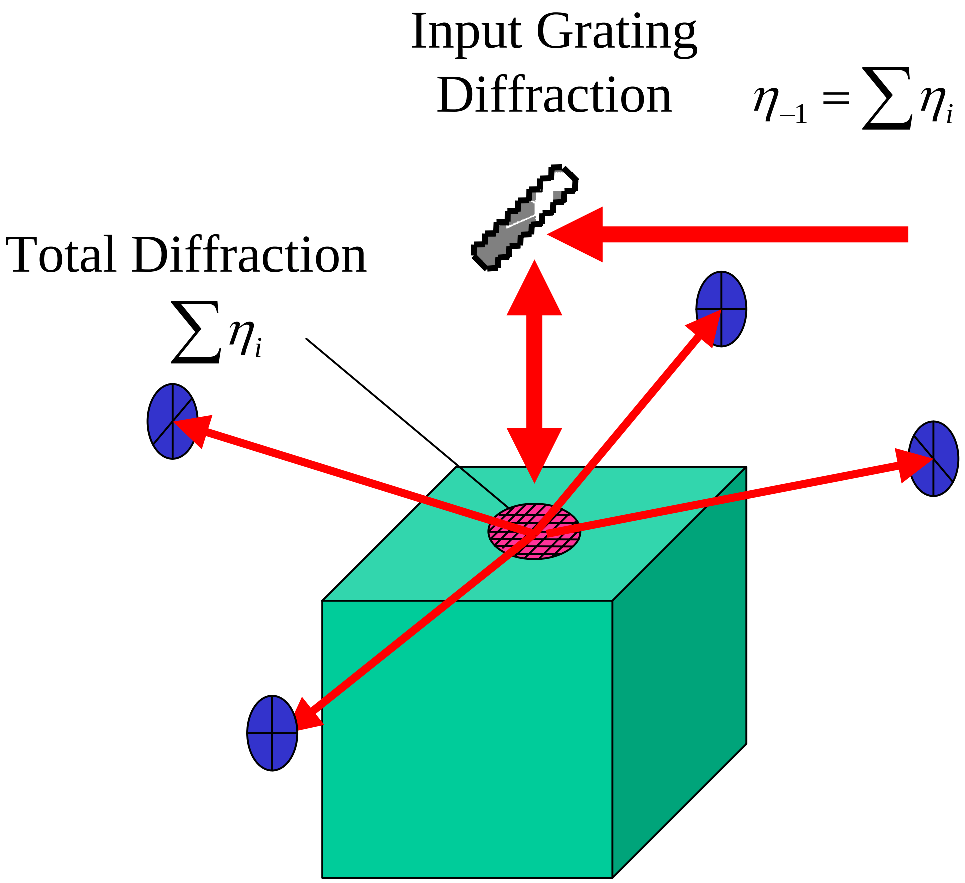
Impedance Matched Grating Cavity for Full Use of Laser Power

Select input grating diffraction efficiency to be the same as the total diffraction efficiency at proof mass grating

$$I_{\text{Reflection}} = \left(\frac{\sqrt{\eta_{-1}} - \sqrt{\sum \eta_i}}{1 - \sqrt{\eta_{-1}\left(\sum \eta_i\right)}} \right)^2 I_{in}$$

$$= 0, \quad if \quad \boxed{\eta_{-1} = \sum \eta_i}$$

$$I_{\text{Transmission}} = I_{in}$$



Input Grating Diffraction

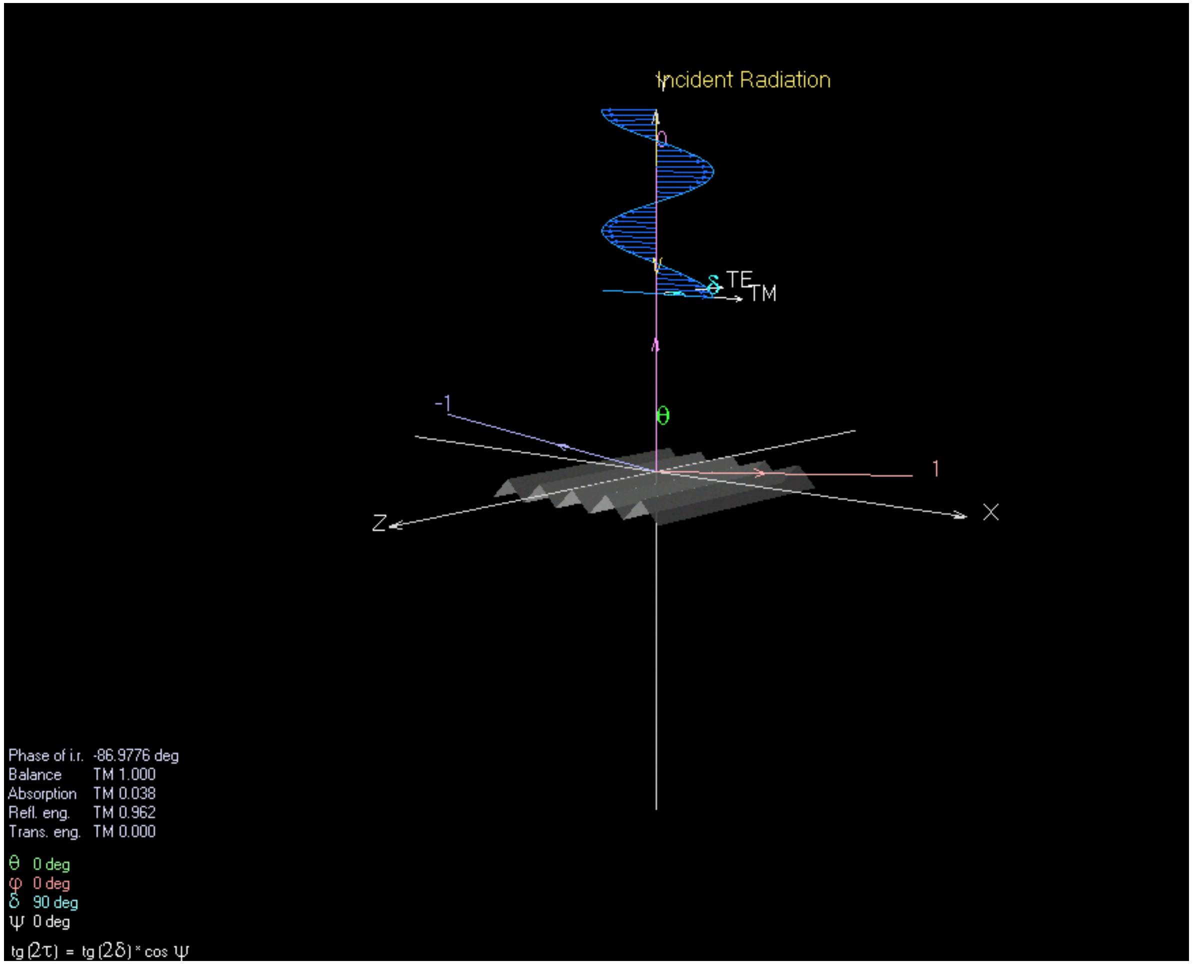
$$\eta_{-1} = \sum \eta_i$$

Total Diffraction

$$\sum \eta_i$$

Grating Design Configuration

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



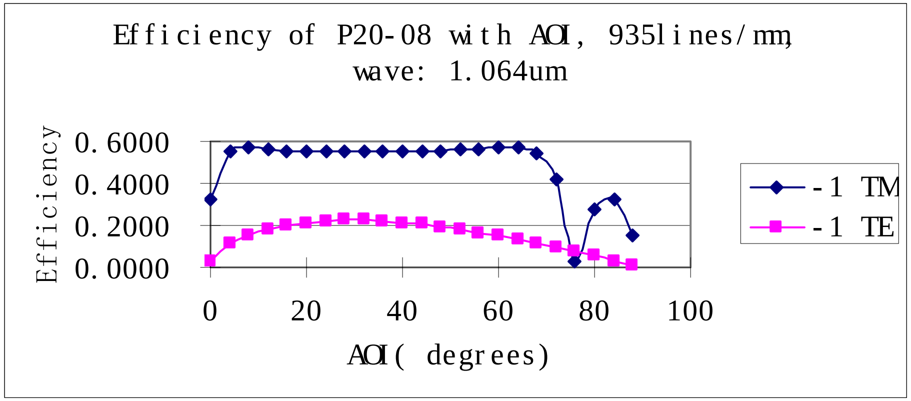
```
Phase of i.r.  -86.9776 deg
Balance        TM 1.000
Absorption     TM 0.038
Refl. eng.     TM 0.962
Trans. eng.    TM 0.000

θ  0 deg
φ  0 deg
δ  90 deg
Ψ  0 deg

tg(2τ) = tg(2δ)*cos Ψ
```

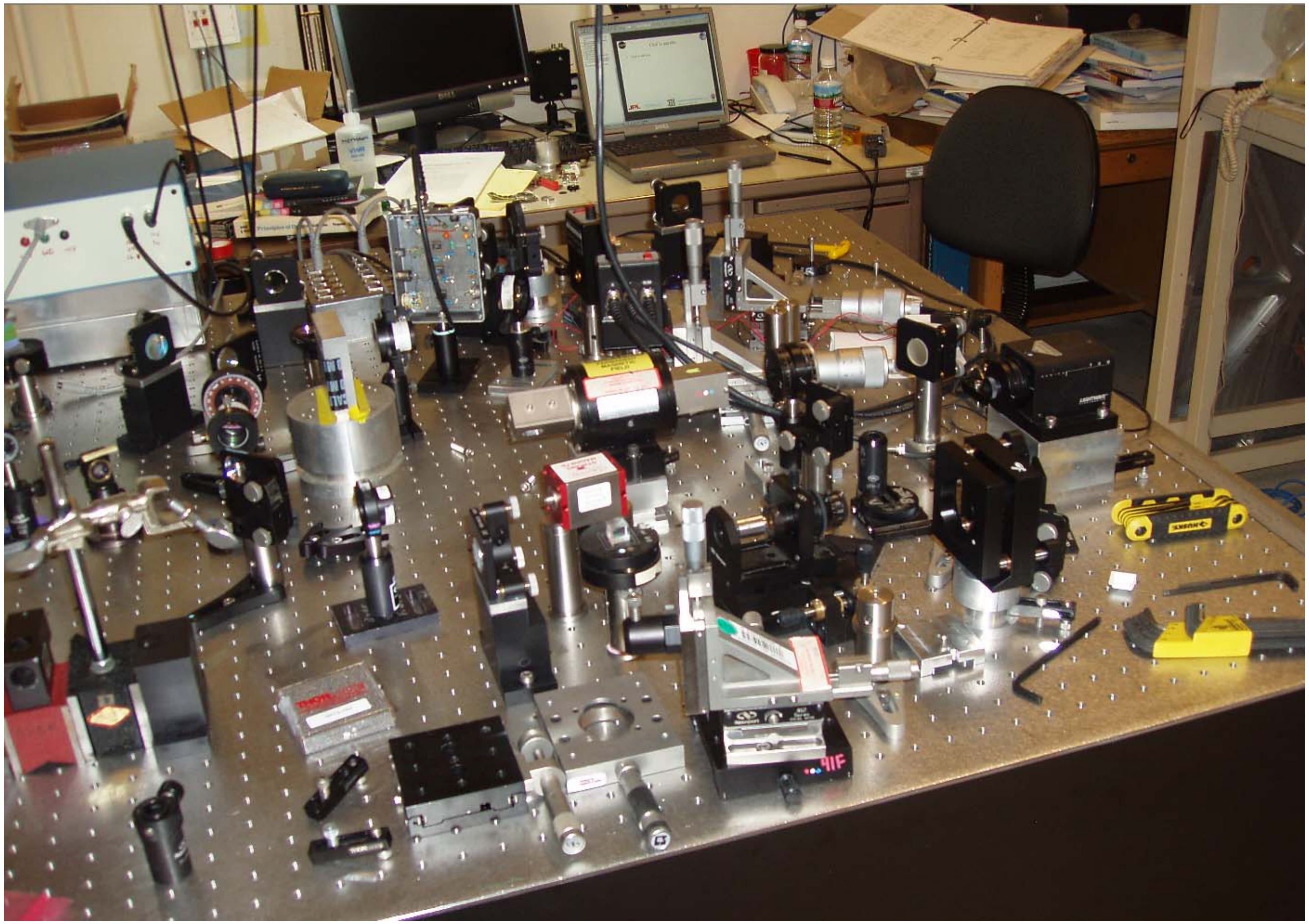
Grating Profile and Diffraction Efficiency

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



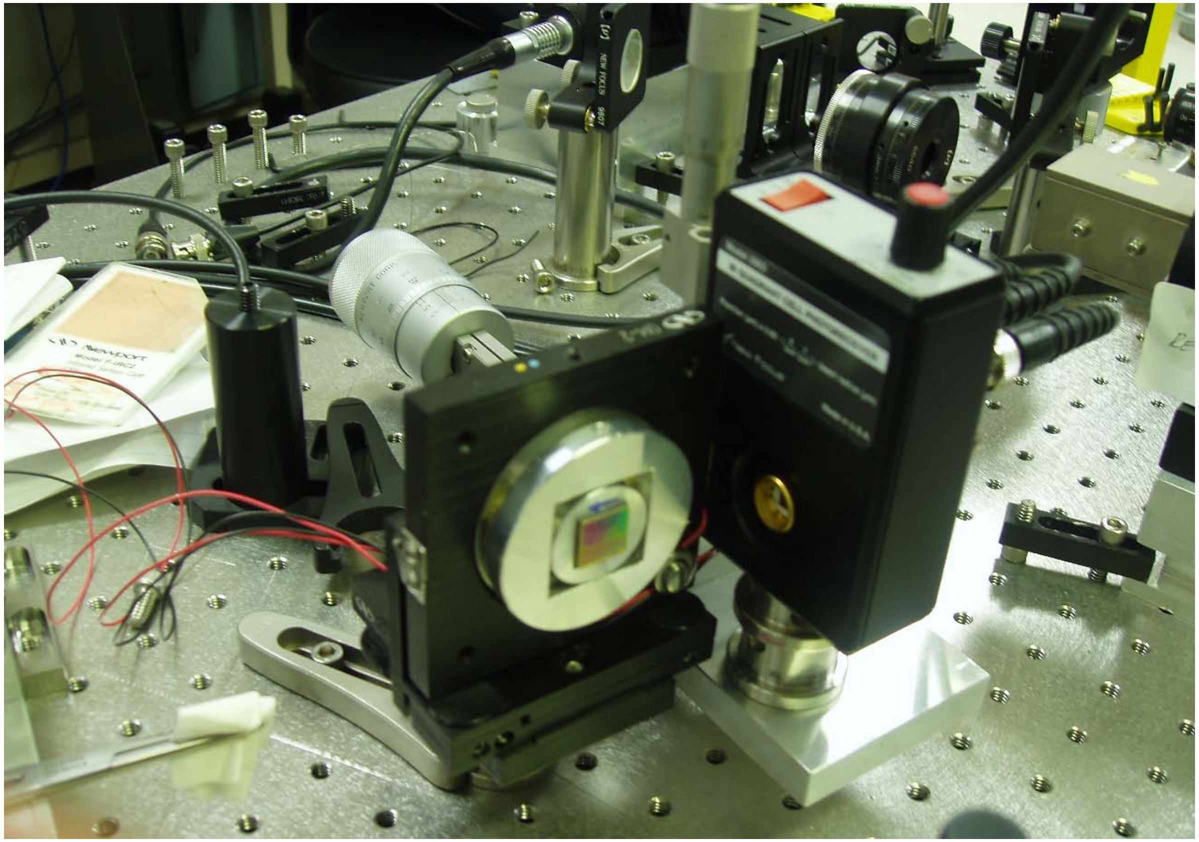
Order #	Eff.	Eff.(TM)	Phase TM	Ampl.TM	Diffr. angl	Az. angle	Polariz. angle, deg	
1	0.29809	0.29809	96.26951	1.722202	84.23187	0	90	
0	0.365359	0.365359	128.0311	0.604449	0	0	90	
-1	0.29809	0.29809	31.32713	1.722202	-84.2319	0	90	

Experimental Setup

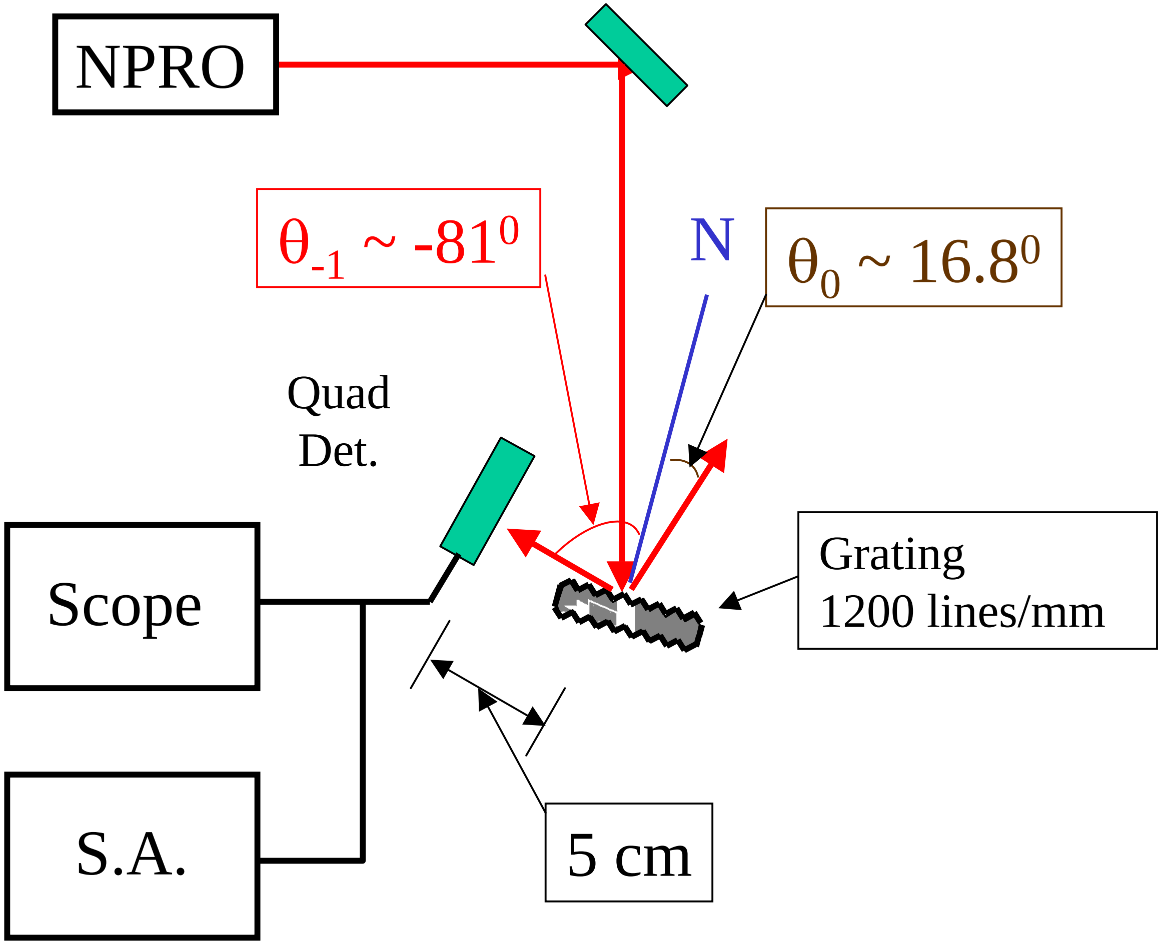


Grating Angular Sensor

- Simple construction
- No extra optics



Grating Angular Sensing Experiment



Sensitivity Enhancement in Preliminary Grating Angular Sensing Experiment

$$\theta_0 = 16.8^0, \quad \theta_{-1} = 81^0$$

Angle Effect Enhancement:

$$F_\theta = \left(\frac{\cos(\theta_0)}{\cos(\theta_{-1})} \right)^2 \approx 38$$

Intensity Variation Enhancement:

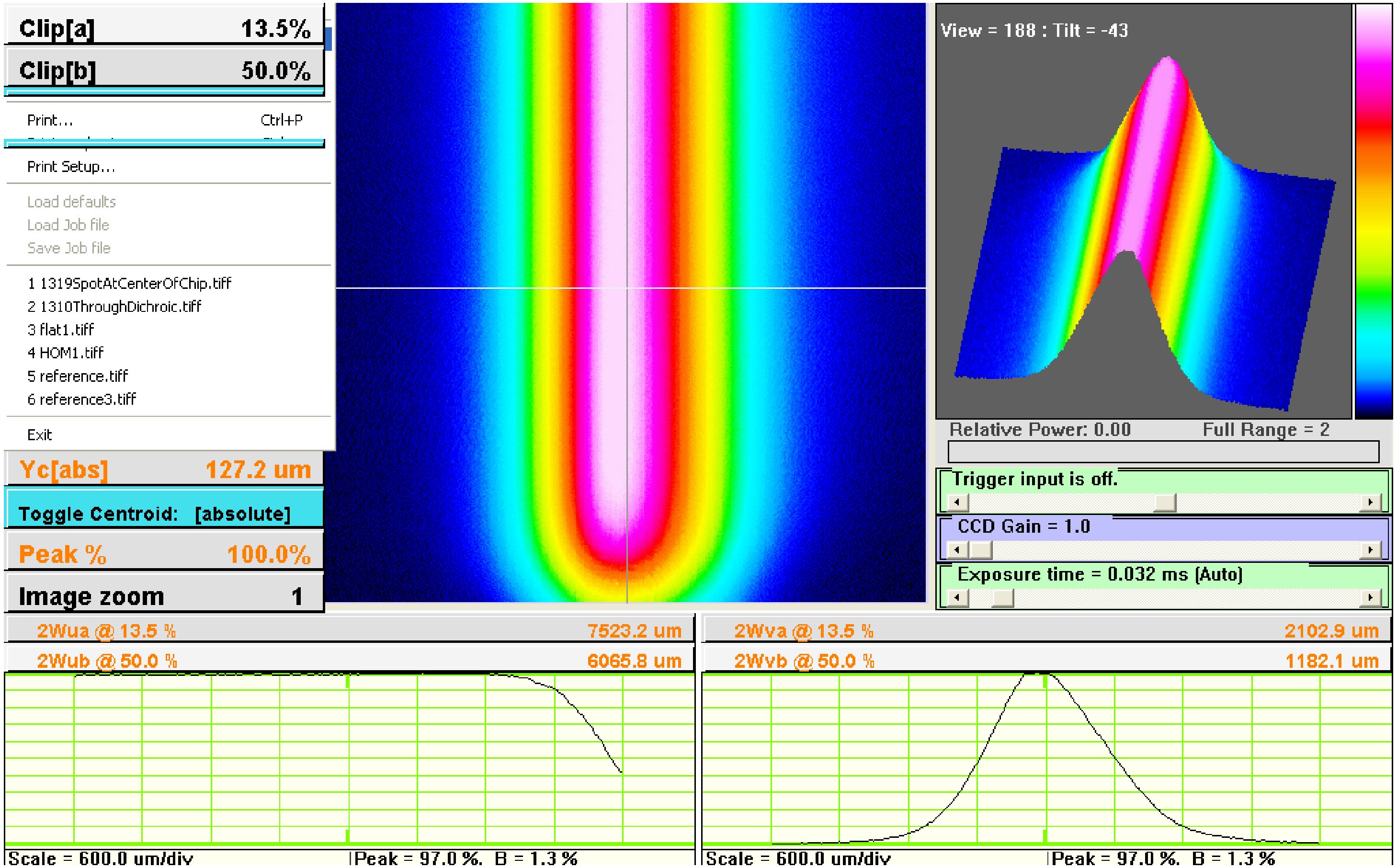
$$F_I \approx 0.45 \times \left(\frac{\cos(\theta_{inc})}{\cos(\theta_m)} \right)^2 \approx 16.8$$

Equivalent length in direct reflection scheme

$$L_G \approx F_\theta L = 38 \times 5 = 190 \text{ cm}$$

$$L_G \approx F_I L = 16.8 \times 5 = 84 \text{ cm}$$

Beam Cross Section Before Grating Compression



Clip[a] 13.5%

Clip[b] 50.0%

Yc[abs] 127.2 um

Toggle Centroid: [absolute]

Peak % 100.0%

Image zoom 1

View = 188 : Tilt = -43

Relative Power: 0.00 Full Range = 2

Trigger input is off.

CCD Gain = 1.0

Exposure time = 0.032 ms (Auto)

2Wua @ 13.5 % 7523.2 um

2Wub @ 50.0 % 6065.8 um

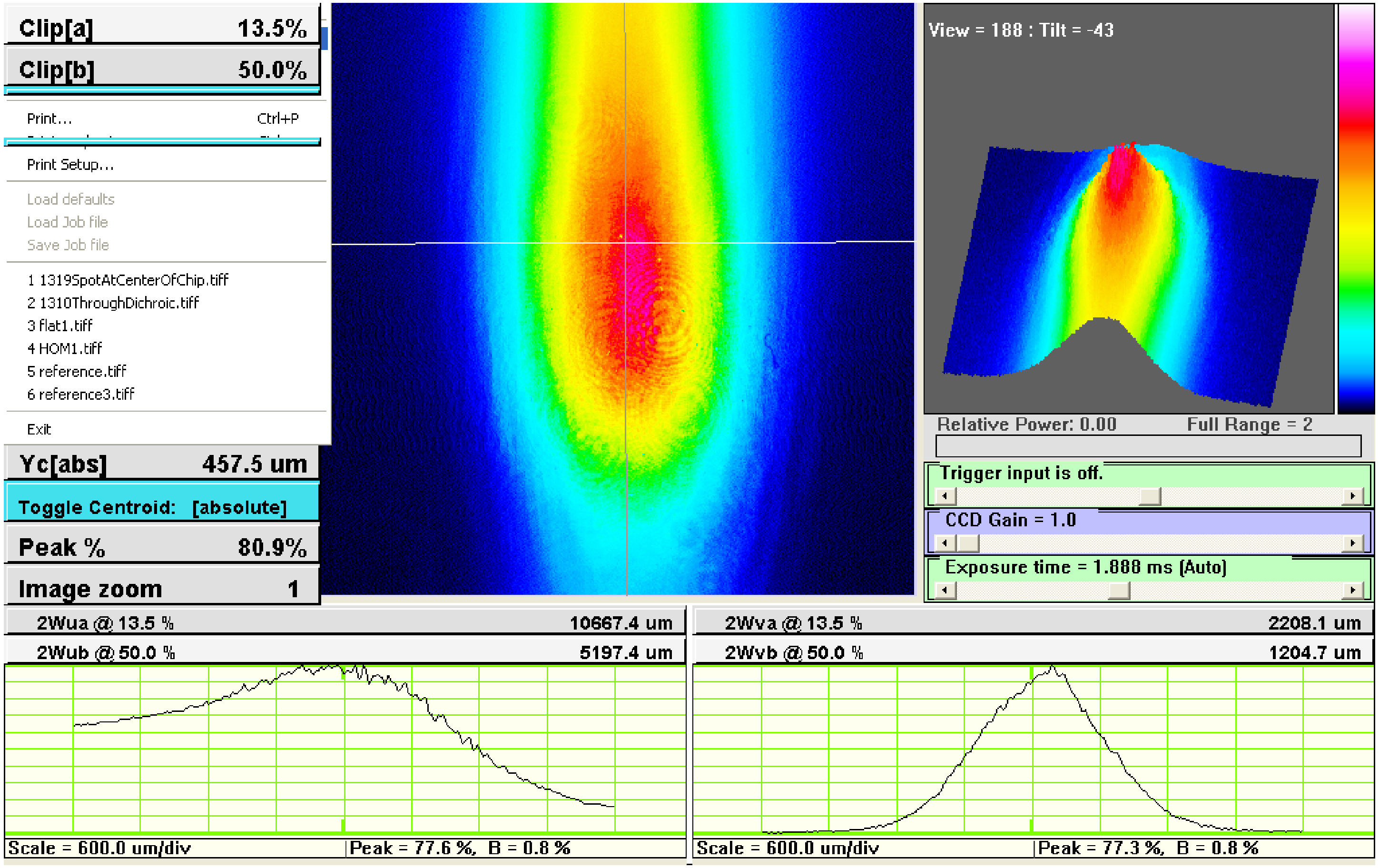
2Wva @ 13.5 % 2102.9 um

2Wvb @ 50.0 % 1182.1 um

Scale = 600.0 um/div Peak = 97.0 %. B = 1.3 %

Scale = 600.0 um/div Peak = 97.0 %. B = 1.3 %

Beam Cross Section After Grating Compression



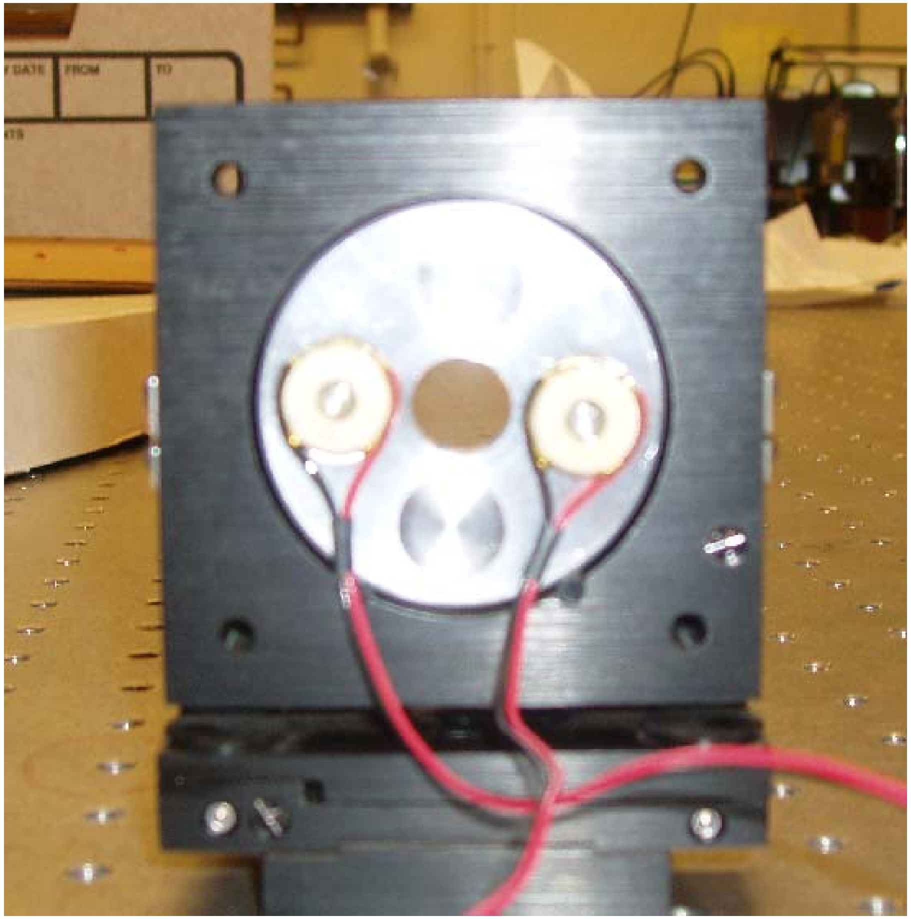
Clip[a] 13.5%
Clip[b] 50.0%
Yc[abs] 457.5 um
Peak % 80.9%
Image zoom 1

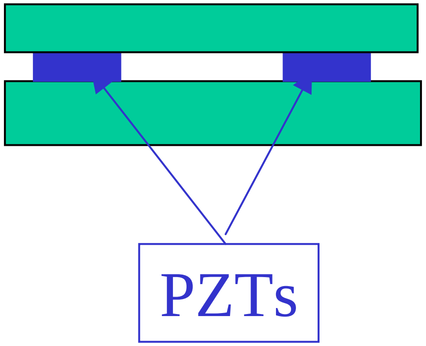
View = 188 : Tilt = -43
Relative Power: 0.00 Full Range = 2
Trigger input is off.
CCD Gain = 1.0
Exposure time = 1.888 ms (Auto)

2Wua @ 13.5 % 10667.4 um
2Wub @ 50.0 % 5197.4 um
Scale = 600.0 um/div Peak = 77.6 %, B = 0.8 %

2Wva @ 13.5 % 2208.1 um
2Wvb @ 50.0 % 1204.7 um
Scale = 600.0 um/div Peak = 77.3 %, B = 0.8 %

Angular Motion Control

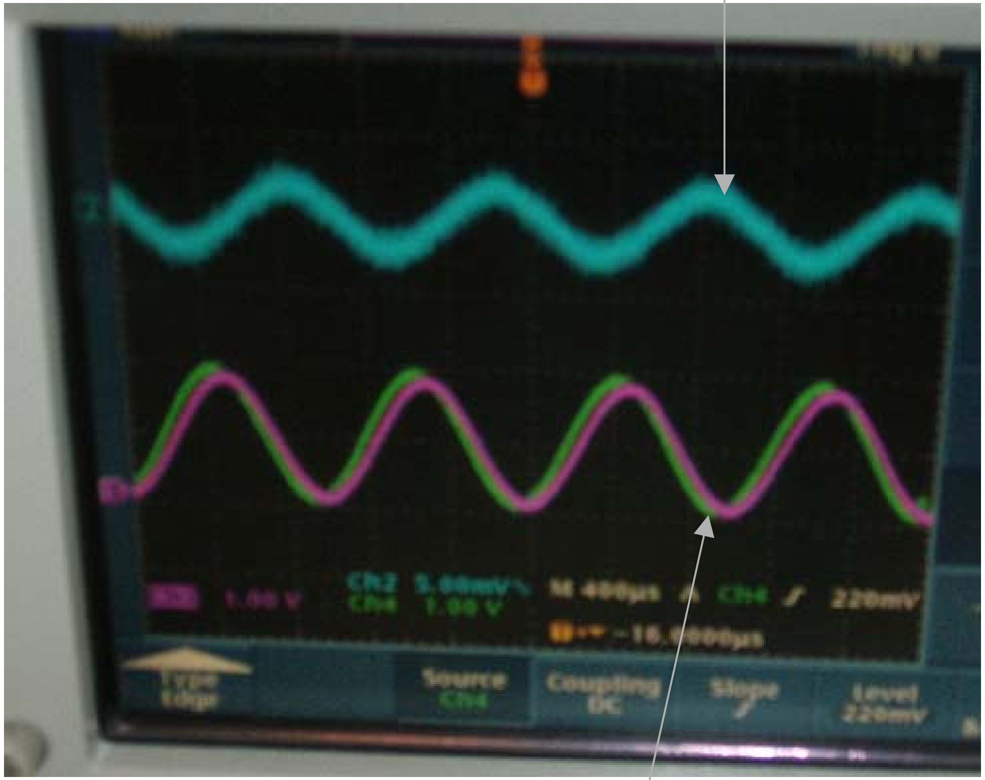




Excursion: ~0.5 μm/100V

Signal from Double-Side, Common-Mode Drive

Quad PD Signal

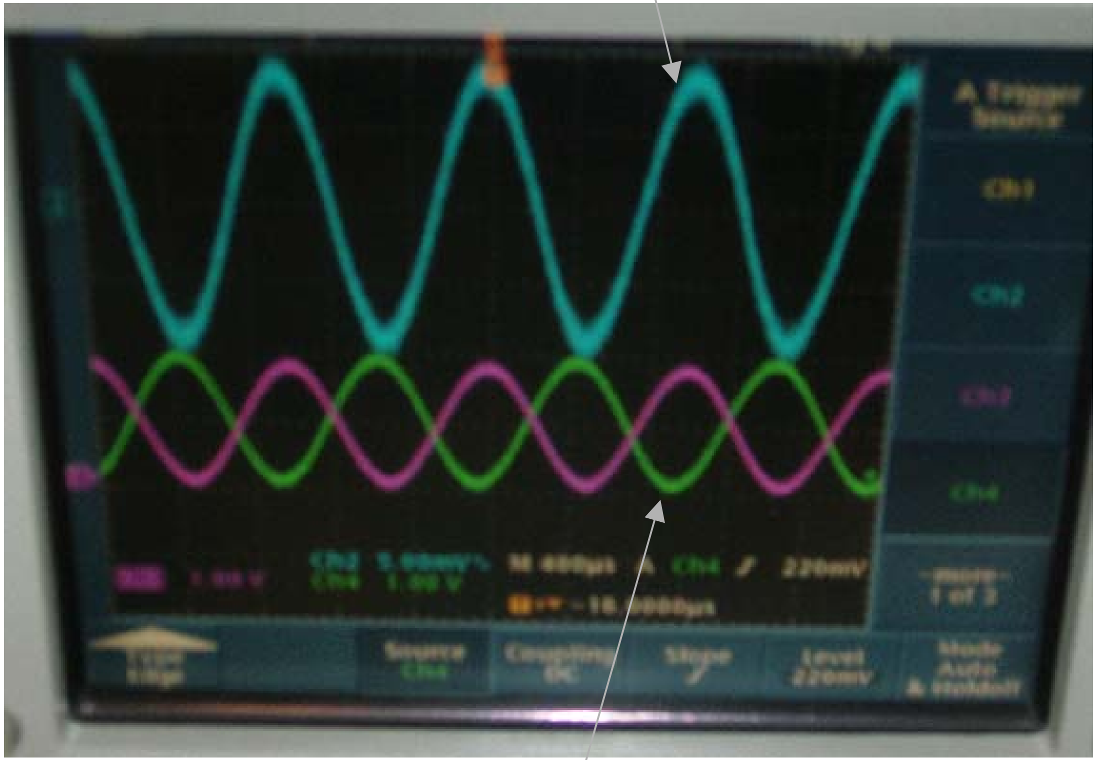


PZT Drive

- Common-mode drive of two PZTs with oscillatory voltages of same phase (~200V)
- PZT displacement 1 μm
- Signal mostly from grating rotation due to asymmetry in system
- Signal amplitude 10 mV

Signal from Double-Side, Differential Drive

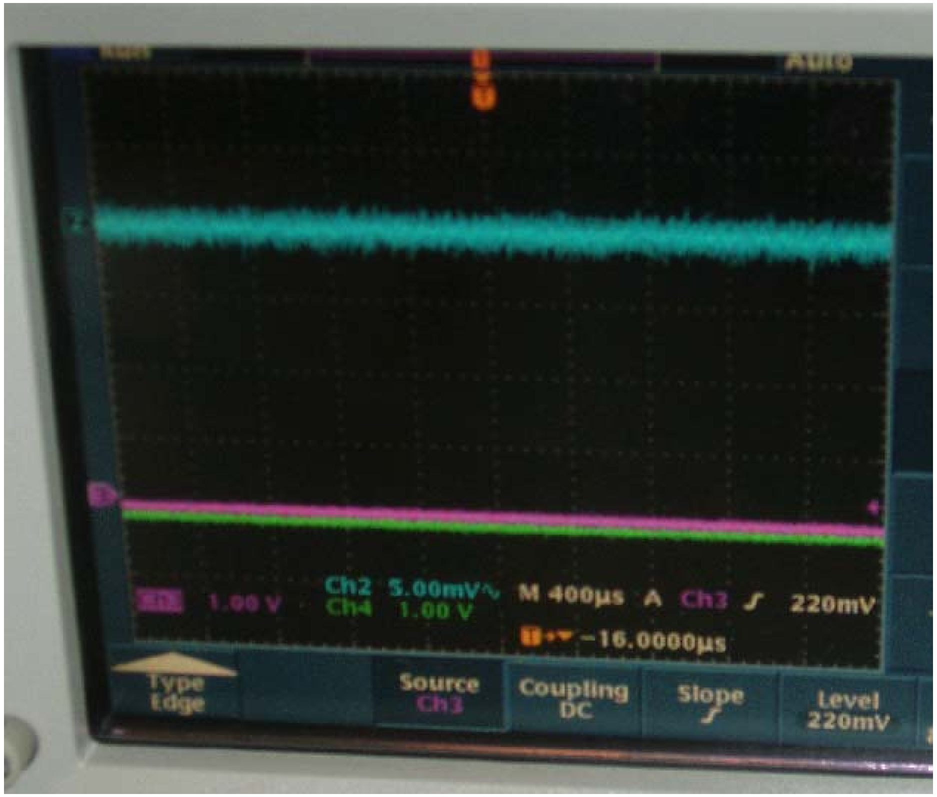
Quad PD Signal



PZT Drive

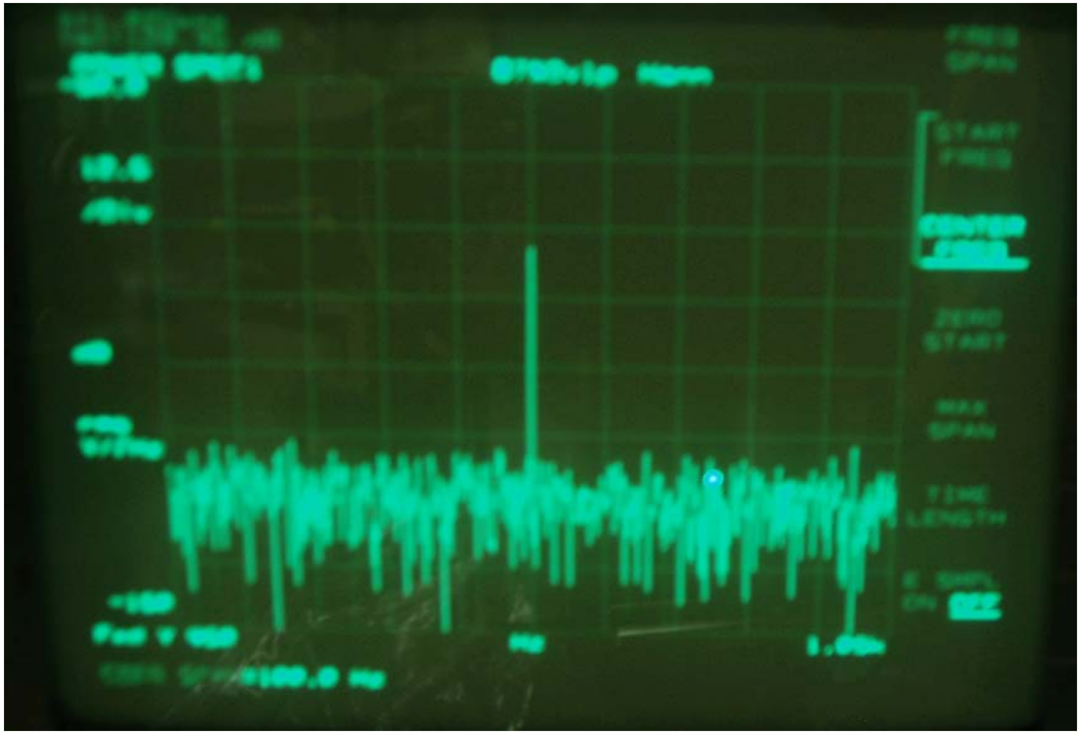
- Differential drive of two PZTs with oscillatory voltages of opposite phase (~200V)
- PZT displacement 1 μm
- Grating rotation 50 μrad
- Signal mostly from grating rotation
- Signal amplitude 20 mV

1/100 Differential Drive



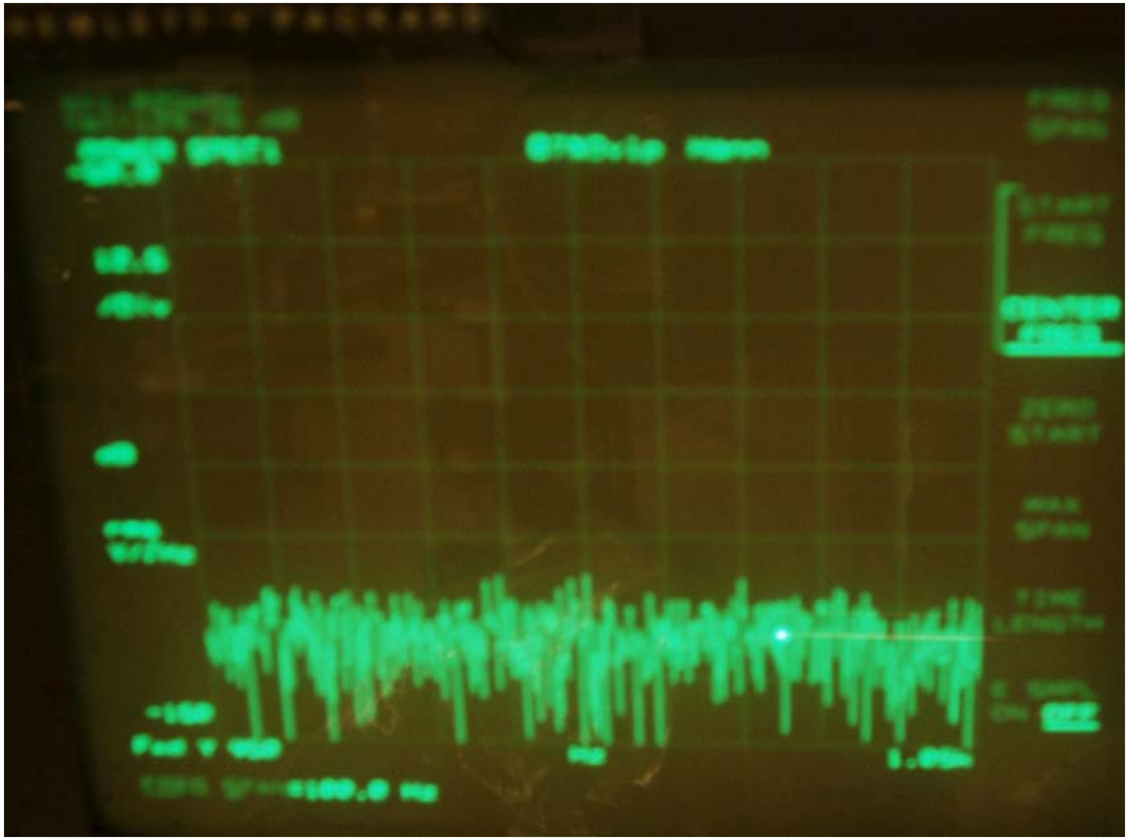
- Differential drive of two PZTs with oscillatory voltages of opposite phase (~2V)
- PZT displacement 10 nm
- Grating rotation 0.5 µrad
- Signal mostly from grating rotation
- Signal observed by FFT spectrum analyzer

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 ~40 dB
- Noise floor level <5 nrad
- FFT Spectrum Analyzer
- Conservative estimate of sensitivity: 10 nrad/Hz$^{1/2}$

Noise Floor When Laser Off



Noise reduction due to absence of 6~8 dB laser intensity noise

Future improvement of light source will further enhance sensitivity

Summary

- A simple, compact angular sensor for possible LIGO interferometer control applications
- 10 nrad/Hz$^{1/2}$ measurement precision demonstrated at 5 cm working distance
- Two-sided detection scheme will provide pure rotation measurement
- Higher measurement precision is possible