Actuation of MEMS Devices using Radiation Pressure

Rafael Kleiman, McMaster University
Hamilton, Ontario, Canada
Ho Bun Chan, University of Florida
John Garno, JPG Design, New Jersey

Panamerican Advanced Studies Institute
MicroElectroMechanical Systems
San Carlos de Bariloche, Patagonia, Argentina
21-30 June 2004

Acknowledgements

- Lucent Technologies, Bell Laboratories
- CFI – Canadian Foundation for Innovation
- OIT – Ontario Innovation Trust
- NSERC – National Science and Engineering Research Council
- CRC – Canada Research Chairs Program

MEMS Activities in Canada

- Optics and Photonics
- RF, Microwave, and Telecommunication Applications
- Micromachining Technologies and Facilities
- Microfluidics (Biomedical, Chemical Sensor Systems, Micro Test Analysis Systems)

Sensors, Actuators, and Microrobotics

- CAD, Modeling, and Simulation
- Testing and Test Structures

Source: CMC – Canadian Manufacturing Corporation

MEMS Activities in Canada

Universities

- Simon Fraser University (BC)
- University of Alberta (AB)
- University of Calgary (AB)
- University of Saskatchewan (SK)
- University of Manitoba (MB)
- Carleton University (ON)
- **McMaster University (ON)**
- Queen's University (ON)
- University of Toronto (ON)
- University of Waterloo (ON)
- University of Western Ontario (ON)
- University of Windsor (ON)
- Concordia University (QC)
- École Polytechnique de Montréal (QC)
- McGill University (QC)
- Dalhousie University (NS)

Corporations

- Bookham Technology
- Centre for Large Space Structures and Systems CLS3 Inc.
- COM DEV Ltd., R&D department
- DALSA Semiconductor
- Infolytica Corporation
- Integrated Engineering Software Sales Inc.
- i-STAT Corp
- JDS Uniphase Corporation, R&D (Strategic Research)
- Medtronic of Canada Limited
- Micralyne Inc.
- Optenia
- SUSS MicroTec, Inc.
- Umech Technologies, LLC
- Xerox Research of Canada

National Labs and Consortia

- Canadian Manufacturing Corporation
- Communications Research Centre
- INO, Photonic Materials and Processes
- National Research Council / Institute for Microstructural Sciences
- Photonics Research Ontario

Source: CMC – Canadian Manufacturing Corporation

MEMS Activities at McMaster

- Radiation pressure experiments (1)
- Ultra-low-force Sensor development (1)
- MEMS integrated optics (2)
- III-V MEMS devices and systems (1)
- Adaptive Optics (1)
- Laser micromachining for new materials (2)
- “nanopower” for ubiquitous sensing (1)
- Communication to ubiquitous sensors (2)
- Novel microfluidic applications (2)
- Biomedical applications (3)

CEMD – Research Fabrication facility

BIMR – Materials and Characterization

HHS – Medical School and research on campus

Outline

Motivation

Background:

- history of radiation pressure experiments
- laser tweezer experiments

Radiation pressure vs. thermal effects

Measurement system/Experimental design

Measurement theory/Circuitry

Present Data

Conclusions

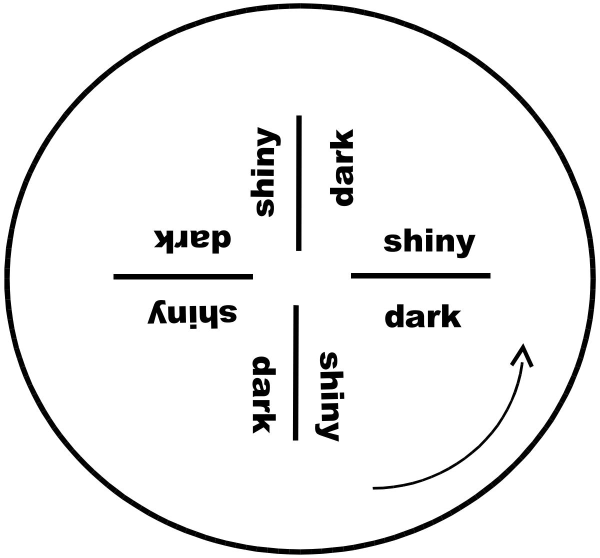
Motivation

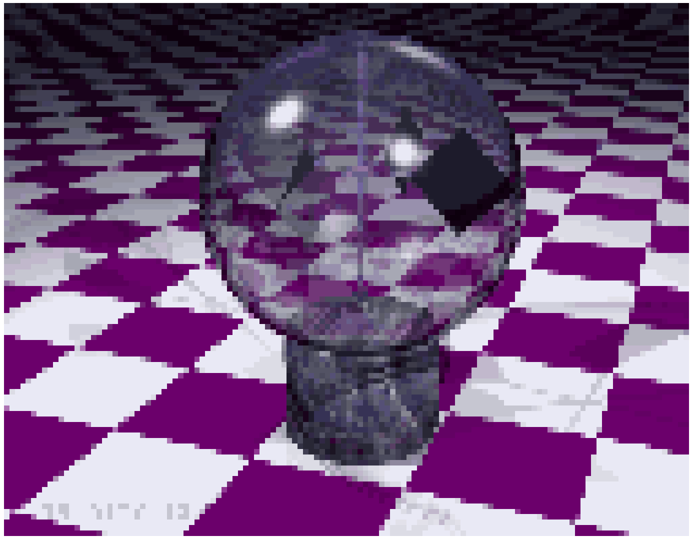
- Connection to optical tweezer experiments
- Understand role of radiation pressure in Optical MEMS devices
- Study physics of Casimir effect using real photons instead of virtual ones – allows the effects to be controlled and studied, including spectroscopically
- Study and utilize plasmon effects to generate enhanced forces on MEMS devices
- Framework for implementing optical computing
- Framework for studying macroscopic quantum entanglement

Radiation Pressure Experiments

A brief history of radiation pressure experiments:

- 1864 - Maxwell, pressure on reflection = 2I/c
- 1873 - Sir William Crookes - "Crookes's Radiometer", turns the wrong way for radiation pressure (Maxwell refereed the paper)
- dark side hotter than shiny side → more pressure, Maxwell showed this is incorrect, just heat flow
- 1879 - Reynolds - submitted paper on "thermal transpiration", flow of gas through porous plates with ΔT, Maxwell refereed it, liked the ideas but not the math
- 1879 - Maxwell submitted "*On stresses in rarified gases arising from inequalities in temperature*", crediting Reynolds, and then died
- 1881 - Reynolds paper was published
- 1901 - P. Lebedev, and E. Nichols & G. Hull, measure radiation pressure in better vacuums





"Light mill", "solar radiometer"

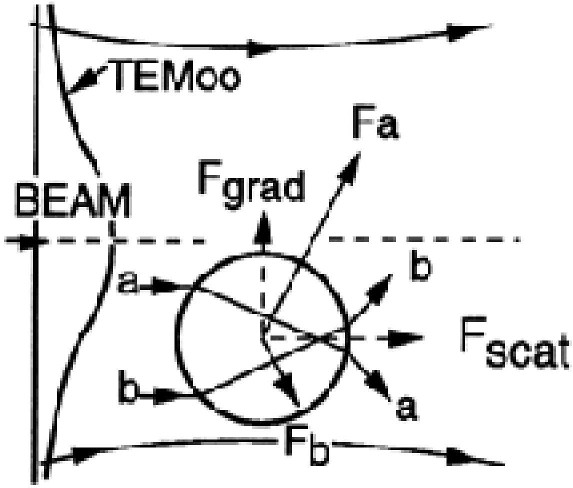
Laser Trapping/Laser Tweezers

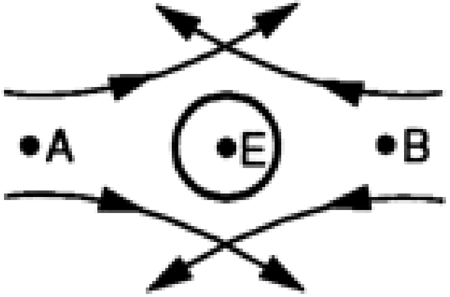
Ashkin, *et al*, at Bell Labs

- 1970: 2-d trapping of latex spheres in water
- 1970: 3d trapping in counter-propagating beams
- 1986: single beam 3-d trapping of atoms...
- 1987-9: application to Biology begins...

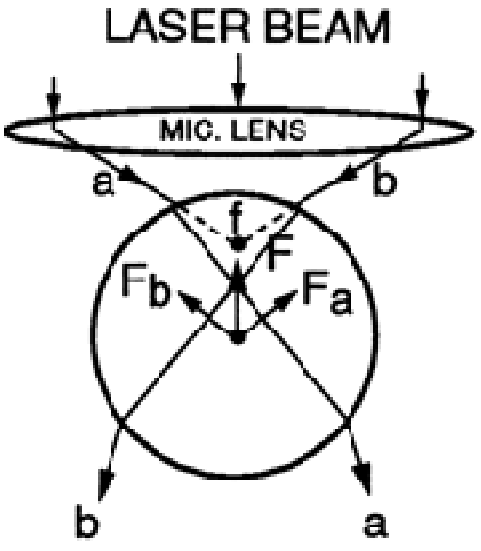
3 perspectives on trapping:

- force: refraction/ray tracing
- energy
- E field gradients





2-BEAM TRAP



TWEEZERS TRAP

All Optical Devices?

- Switching one light beam with another light beam
- Optical computing (perhaps for network)
- Rough comparison to other non-linear media:

$$n = n_0 + n'_2|E|^2 \qquad n'_2 \sim 1.5\chi^{(3)}/\varepsilon_0 n_0$$

$$\Delta n/n_0 = (n'_2/n_0)|E|^2$$

$$n'_2/n_0 \sim 3.7 \times 10^{-23}\ \mathrm{m^2/V^2}, \text{ for } SiO_2$$

$$n'_2/n_0 \sim 3.6 \times 10^{-22}\ \mathrm{m^2/V^2}, \text{ for } CS_2$$

$$\Delta\theta = P_{rad}A/kl = (\varepsilon/Y)|E|^2 \quad \text{optimally}$$

$$\varepsilon/Y \sim 1.3 \times 10^{-22}\ \mathrm{m^2/V^2}, \text{ for Si/polystyrene}$$

- If enhance the effect and make devices smaller/faster gets interesting

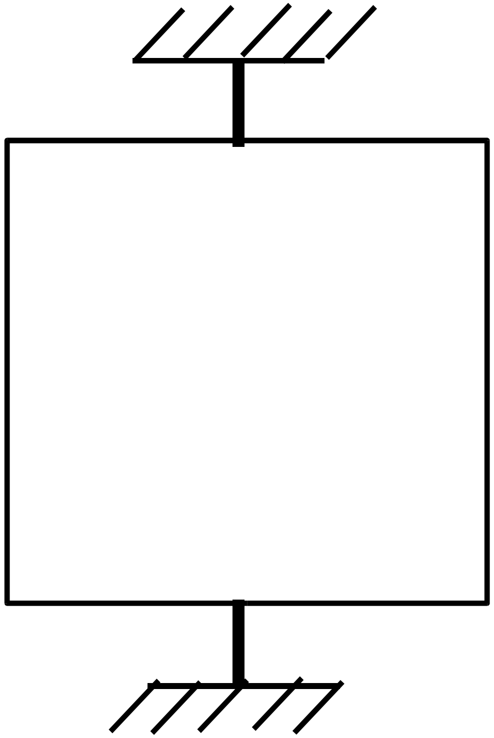
Radiation Pressure *vs.* Thermal effects

Why not just use thermal effects?
How to separate the effects?

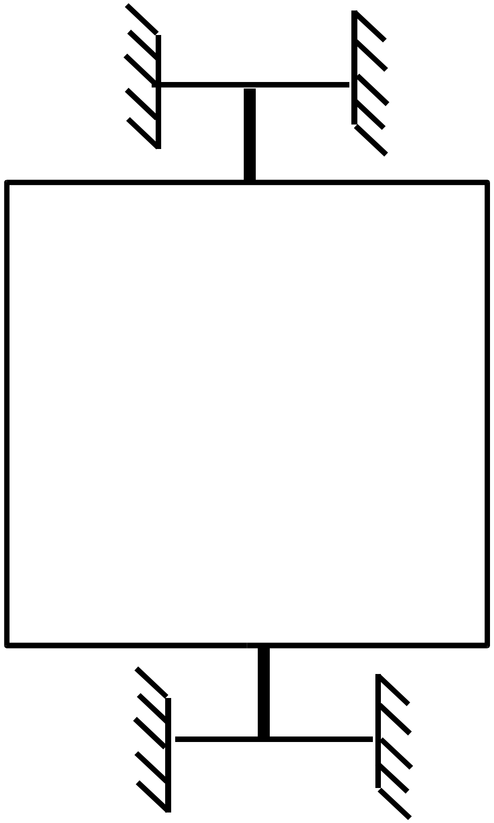
Big parasitic effect that raises a multitude of strategies/design issues

- reduce exposure of metals/semiconductors/absorbing materials
- pull heat away (by increasing coupling to outside)
- design to minimize thermal gradients
- choose wavelength/ materials correctly
- design to go with it (reduce coupling to mode of interest)
- work at frequencies above (thermal time constant)$^{-1}$

Reduce coupling to torsional mode?



Present design

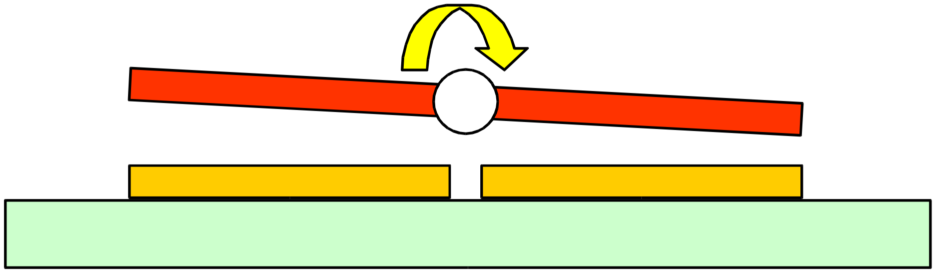


Improved design?

Measurement System Outline

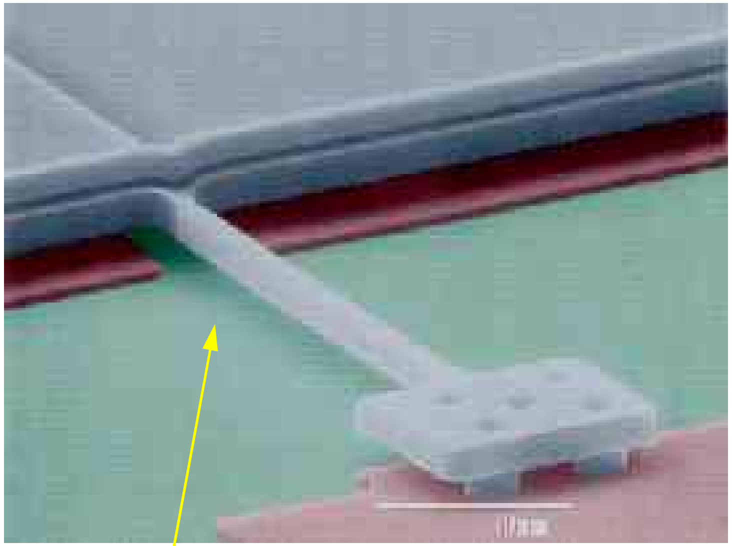
- MEMS device is actuator (and sensor)
- Glue dielectric sphere to MEMS device
  - to mimic laser tweezer experiments (functionally equivalent to a 1-d trap)
  - to minimize heating effects
- Optical design/layout
- HV chamber and vibration isolation
- Low-noise circuitry

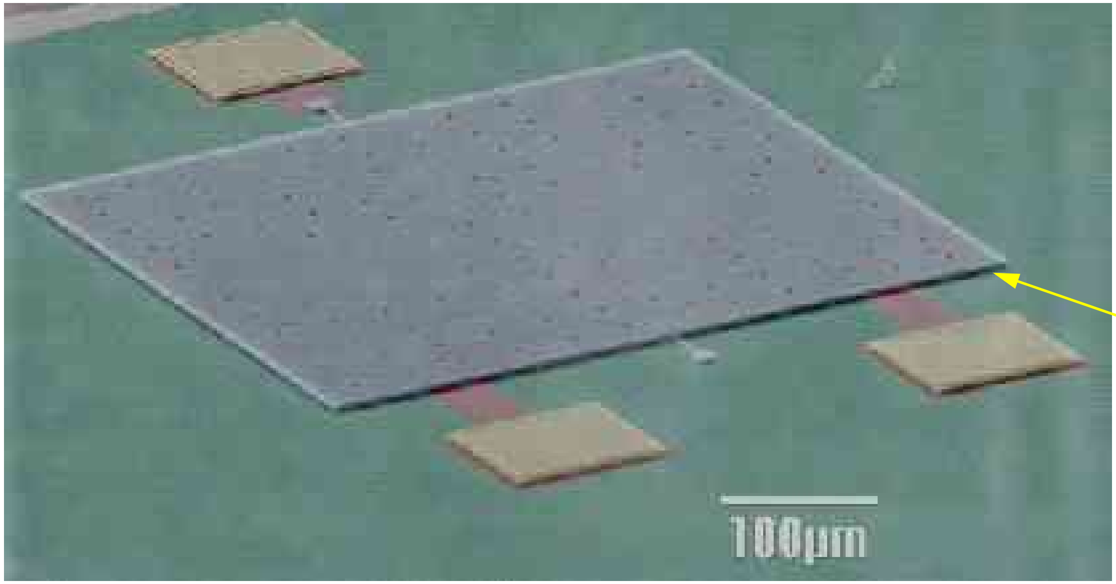
MEMS Force Sensor



$c = 2.1 \times 10^{-8}$ N-m $\quad f_0 \sim 3500$ Hz

$I = 7.1 \times 10^{-17}$ kg m^2 $\quad Q \sim 25000$





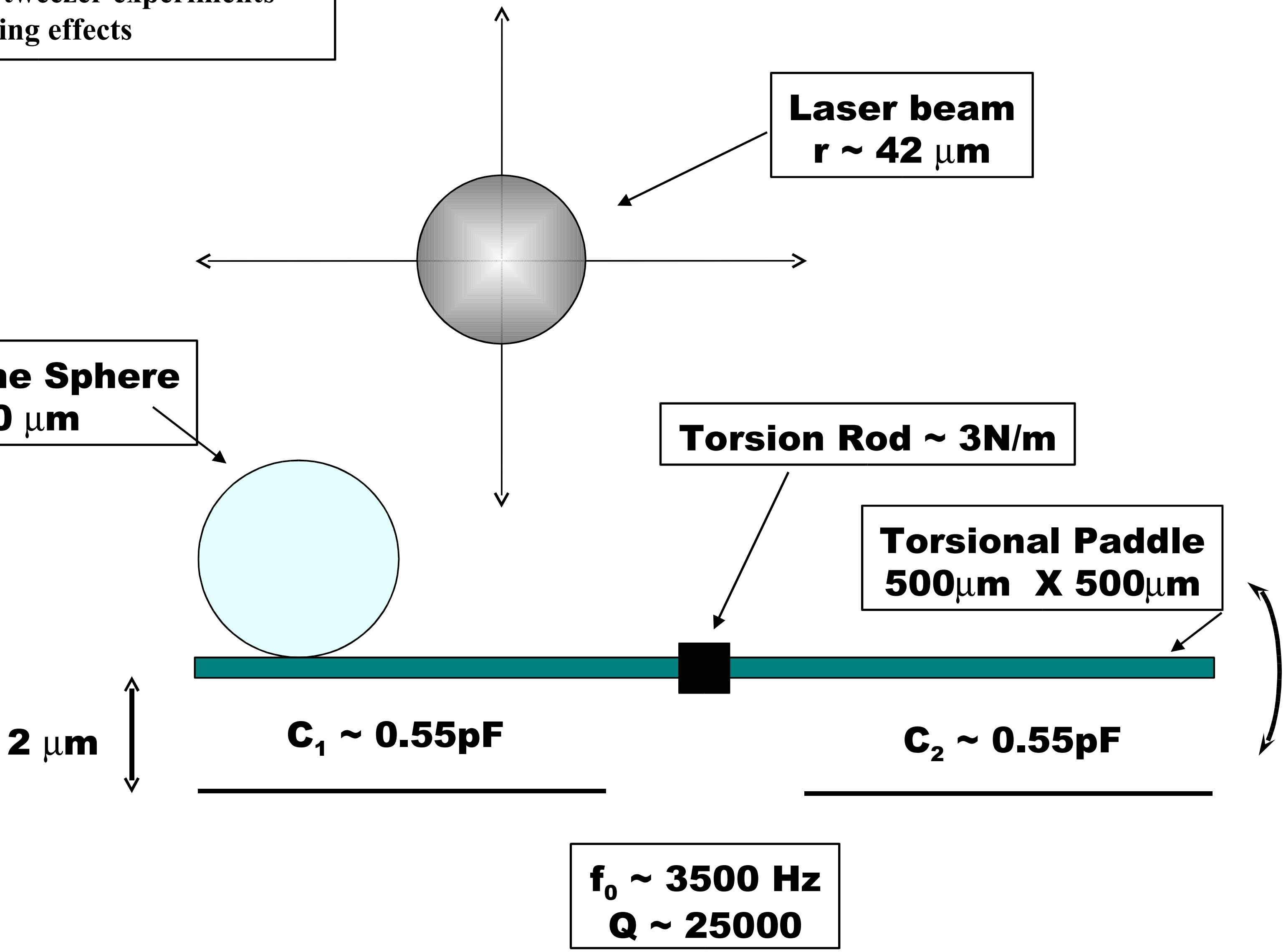
Torsional rod
cross section: 1.5 x 2 μm^2

poly-Si plate:
500 μm x 500 μm x 3.5 μm

H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and Federico Capasso, Science, **291**, 1941 (2001).

Experimental Layout - Force sensor

Note: Use dielectric sphere intentionally:
- to quantify laser tweezer experiments
- to minimize heating effects



Laser beam
r ~ 42 μm

Polystyrene Sphere
r = 50 μm

Torsion Rod ~ 3N/m

Torsional Paddle
500μm X 500μm

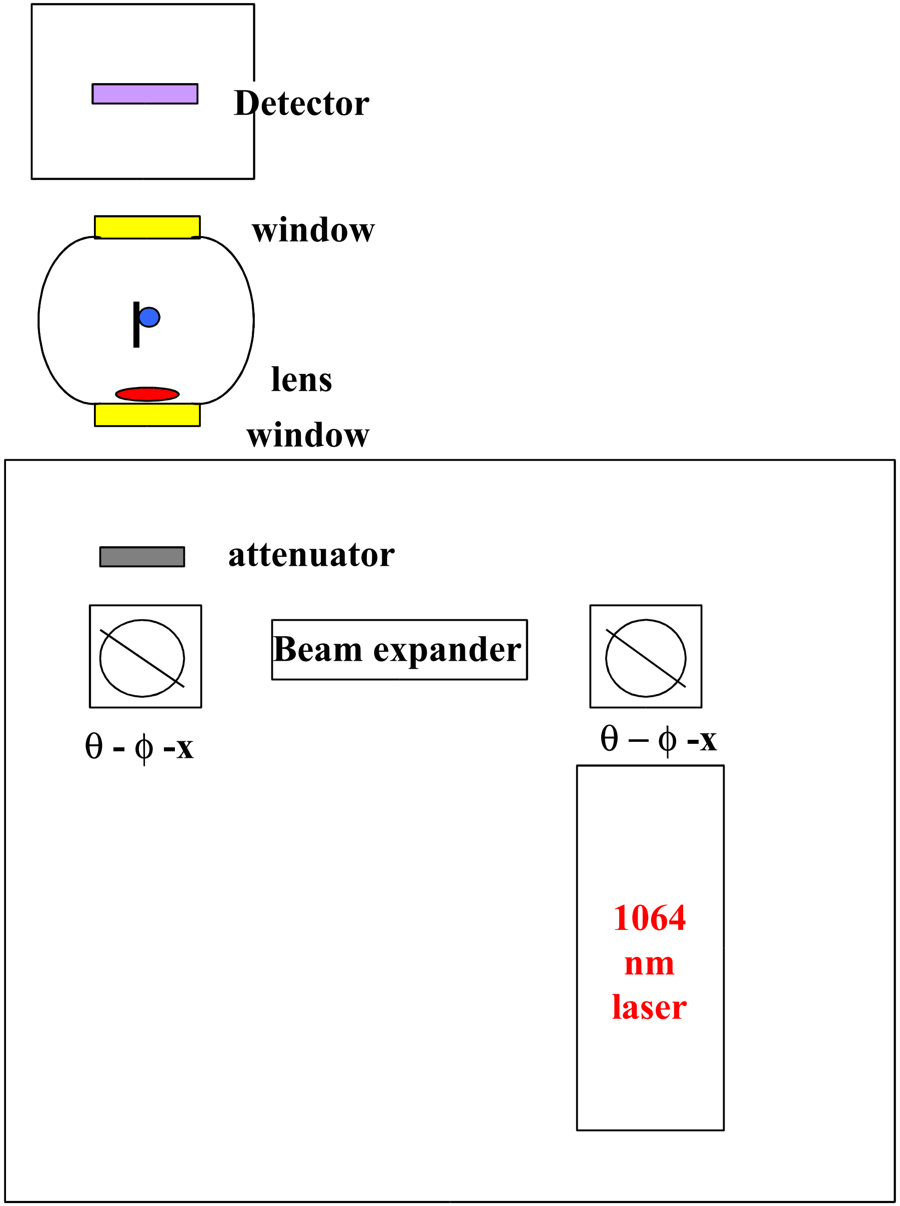
2 μm

C_1 ~ 0.55pF

C_2 ~ 0.55pF

f_0 ~ 3500 Hz
Q ~ 25000

Experimental Layout - Optics

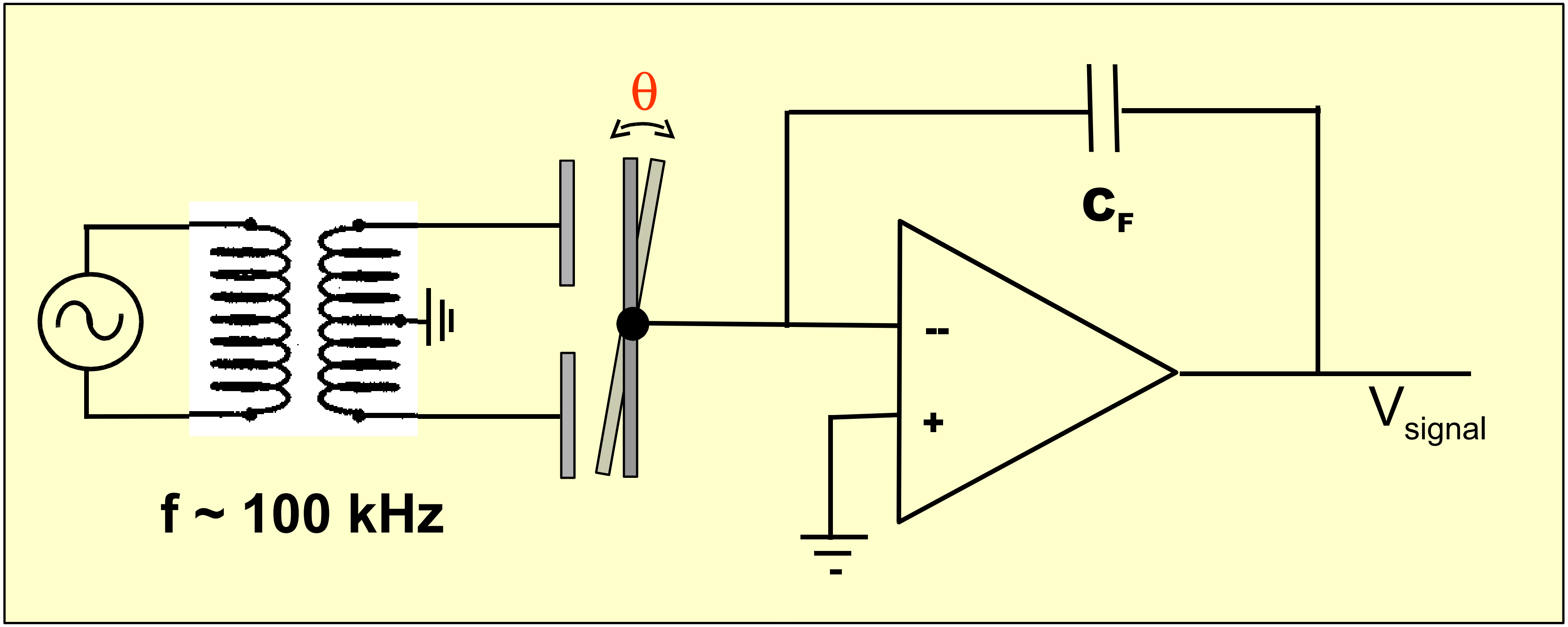


+ HV system
(~10^{-9} Torr)
on vibration
isolation table

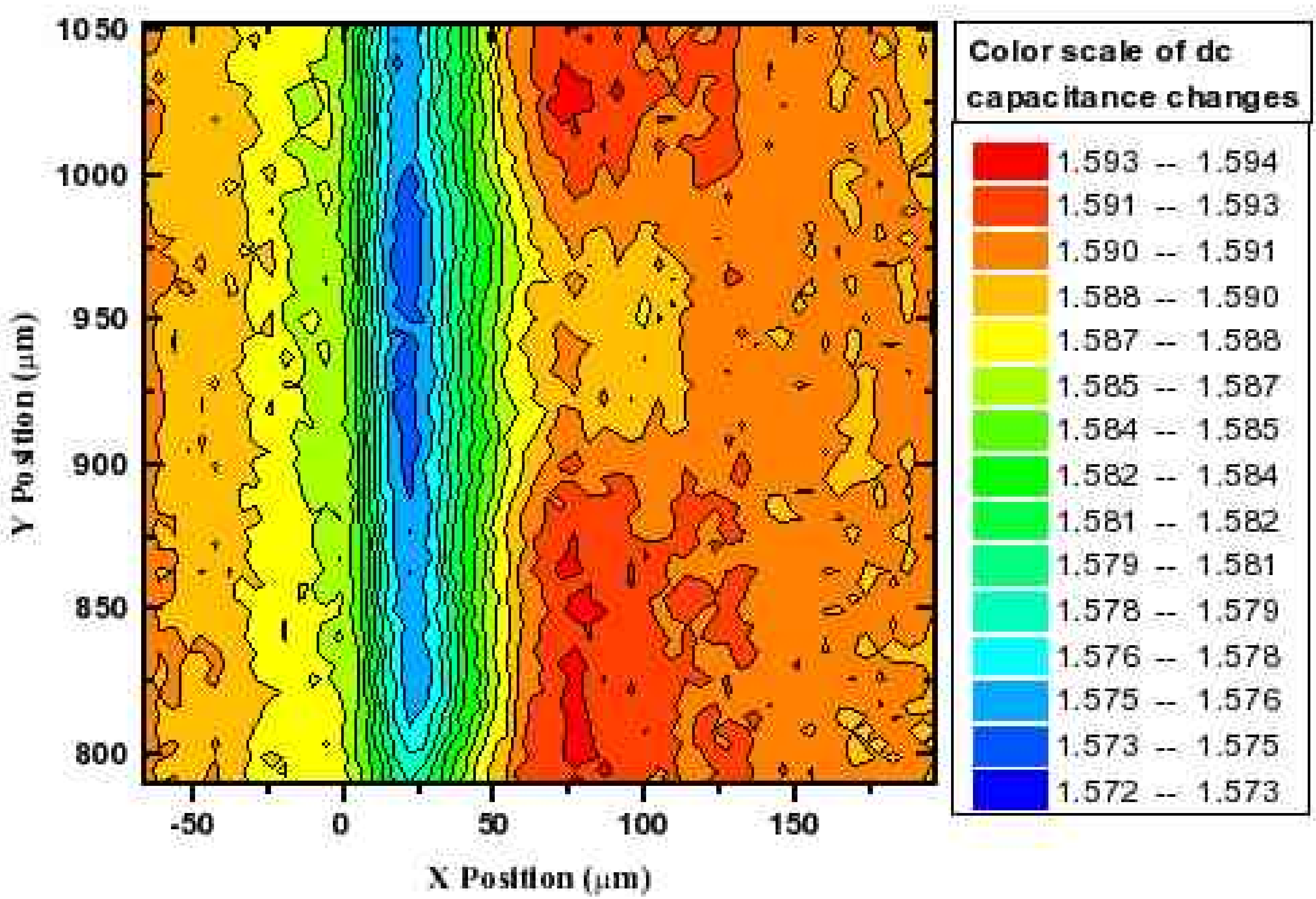
Circuitry for dc Detection

Capacitive detection of torsional motion

For small θ,
$V_{signal} \propto \Delta C$
$\propto \theta$
$\propto \Delta F$



dc Capacitance Shift



Noise in Low Force ac Measurements

- Thermal noise of detector from e_n of input transistor; flat *vs.* frequency
- Thermal noise of oscillator peaked at resonance:

$$f_n \sim (4k_BTkQ/\omega_0)^{1/2}$$

- But signal increases by Q at resonance

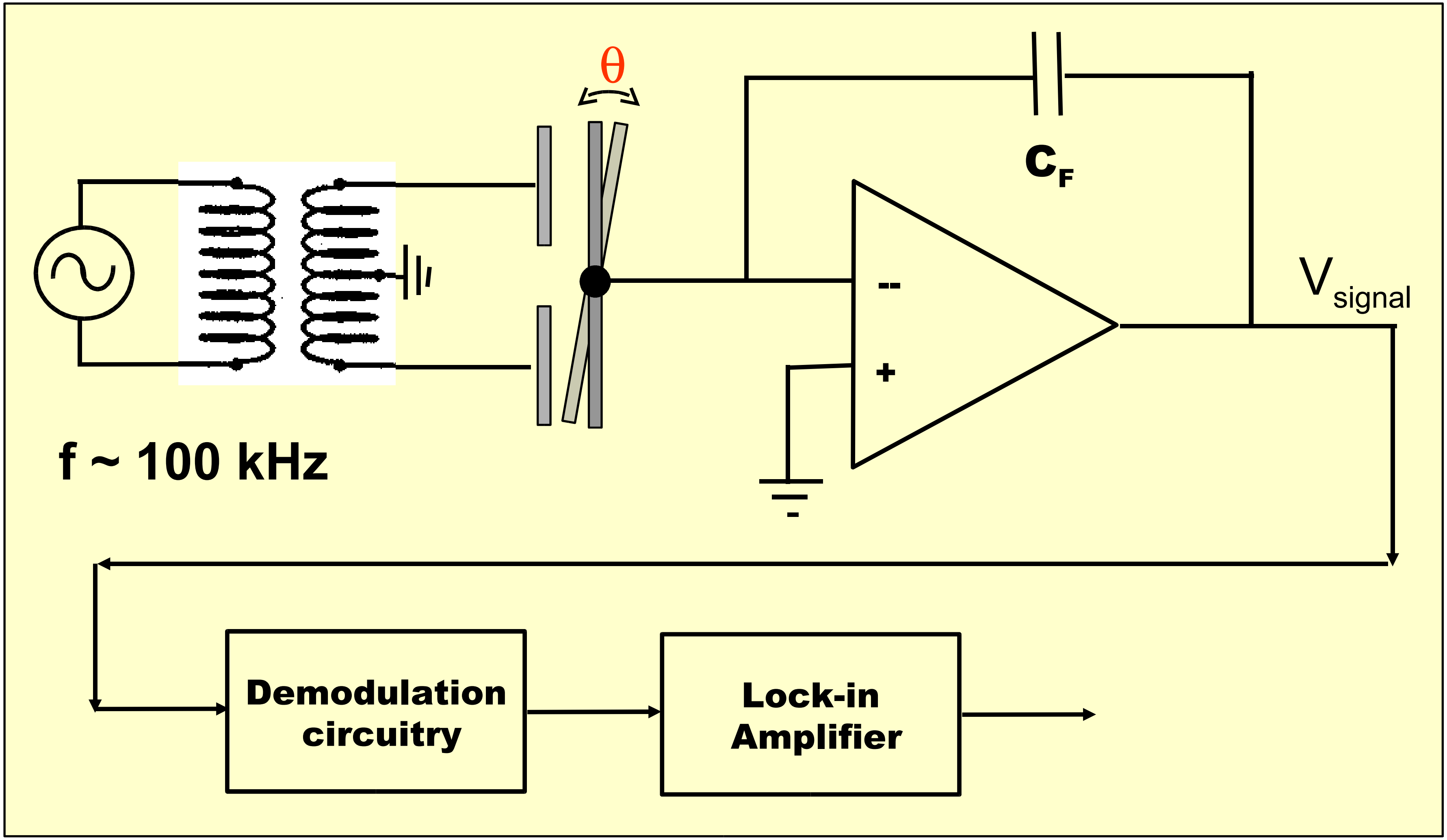
$$f_n' \sim (4k_BTk/Q\omega_0)^{1/2}$$

- ∴ Signal to noise generally improves at resonance
- Want low k, high ω_0, high Q:

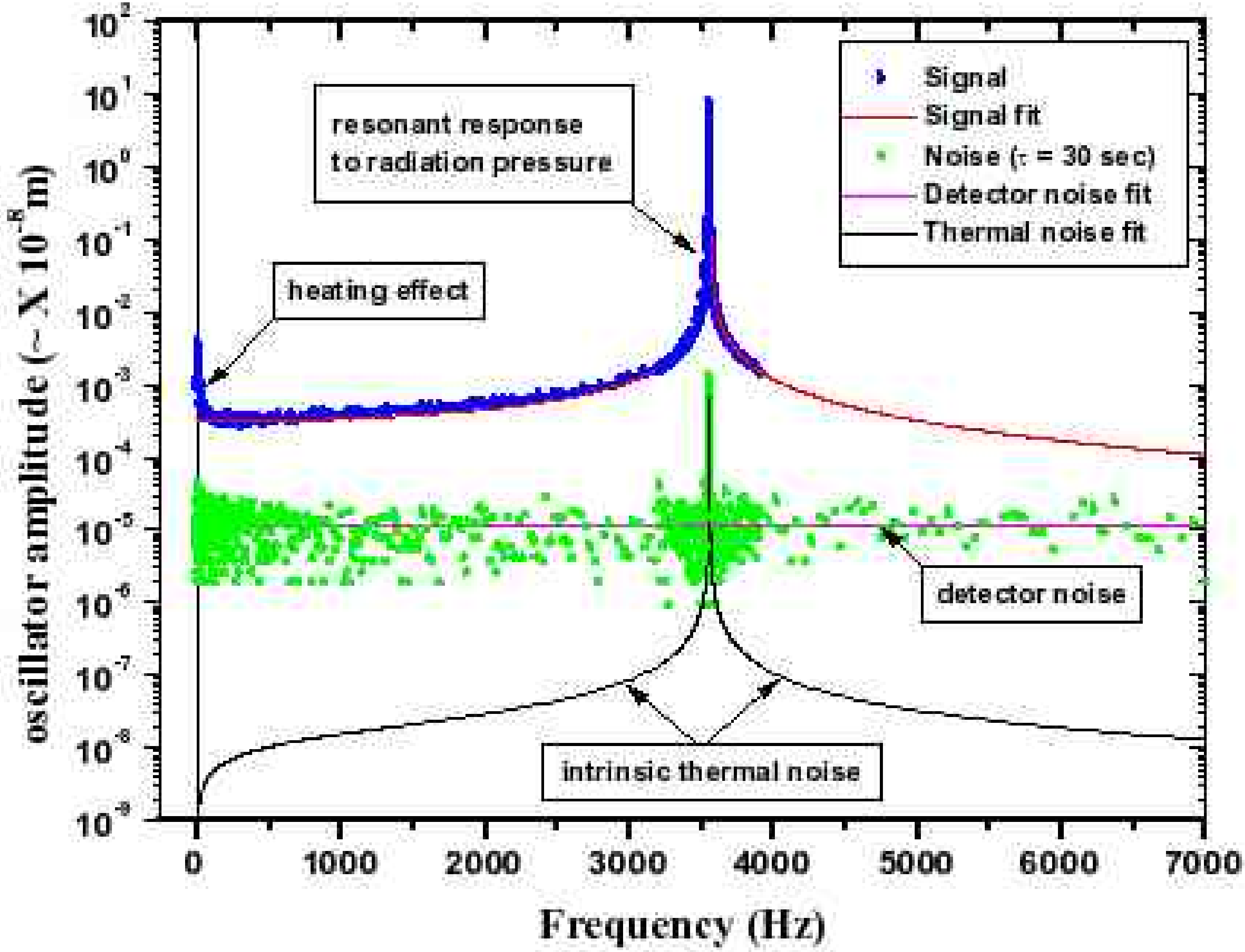
ideal direction for MEMS

Circuitry for ac Detection

Can drive the oscillator electrically or optically and use demodulation circuitry to measure ac components with ~ 10 kHz BW

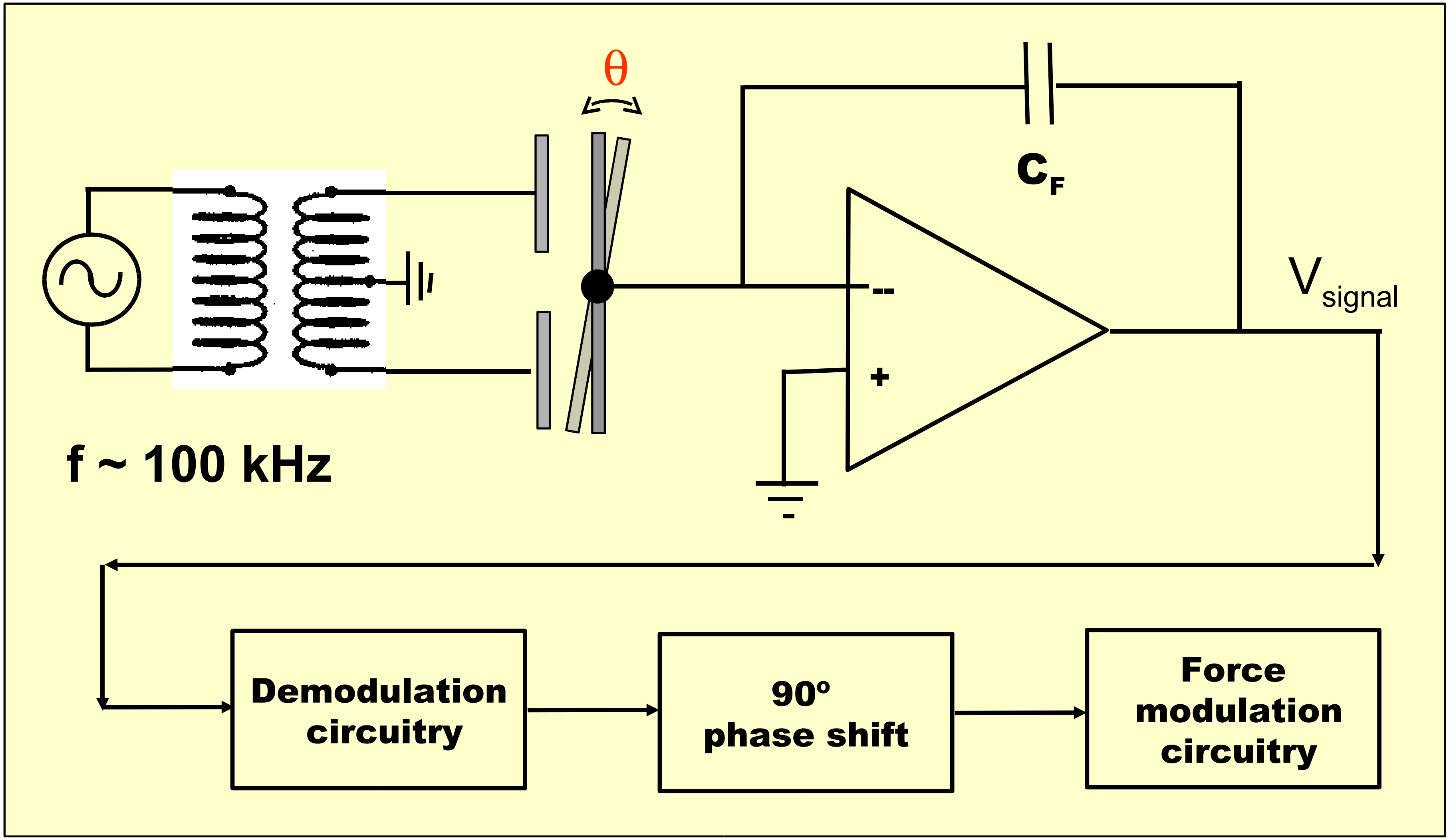


Frequency Dependence

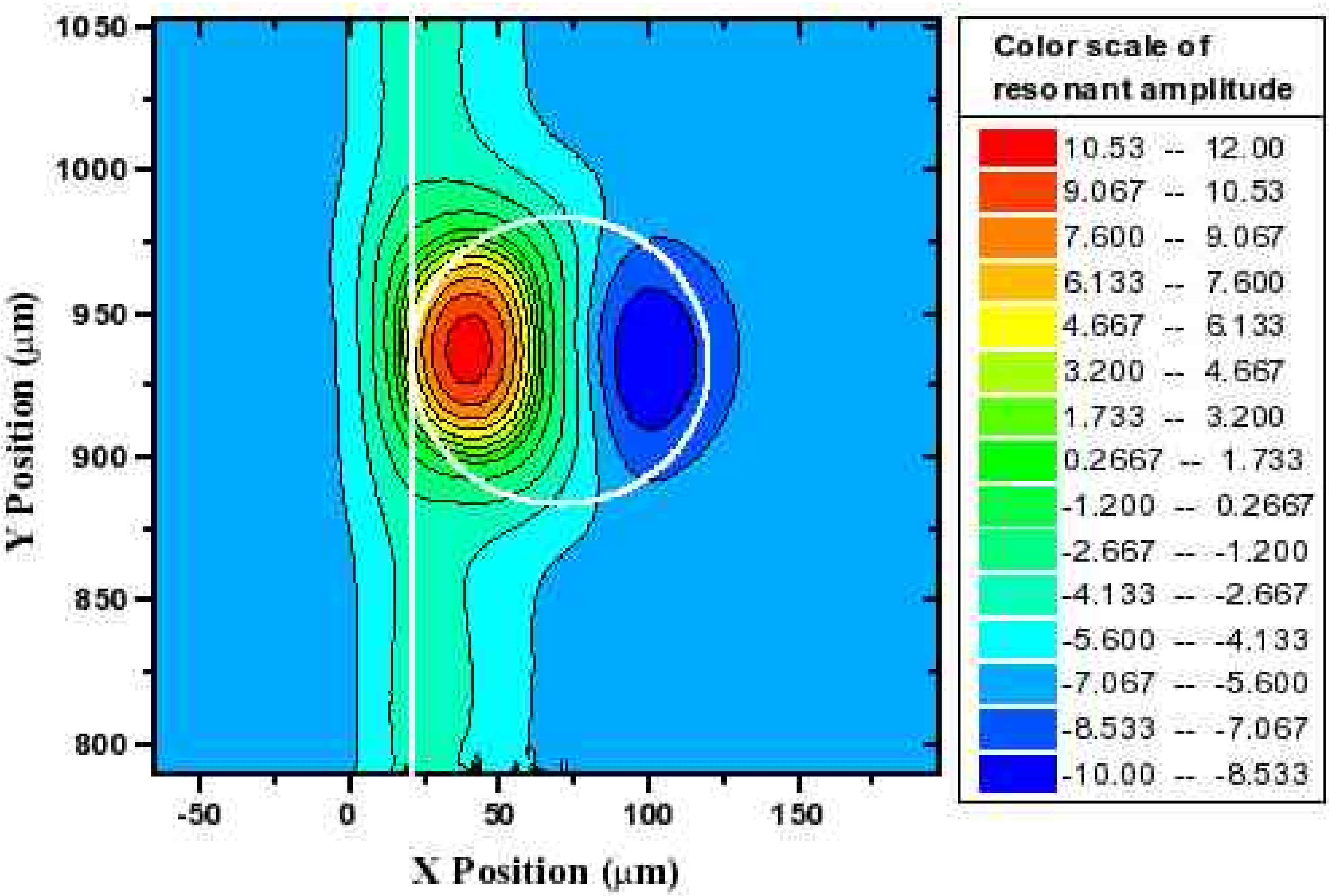


Circuitry for Resonant Detection

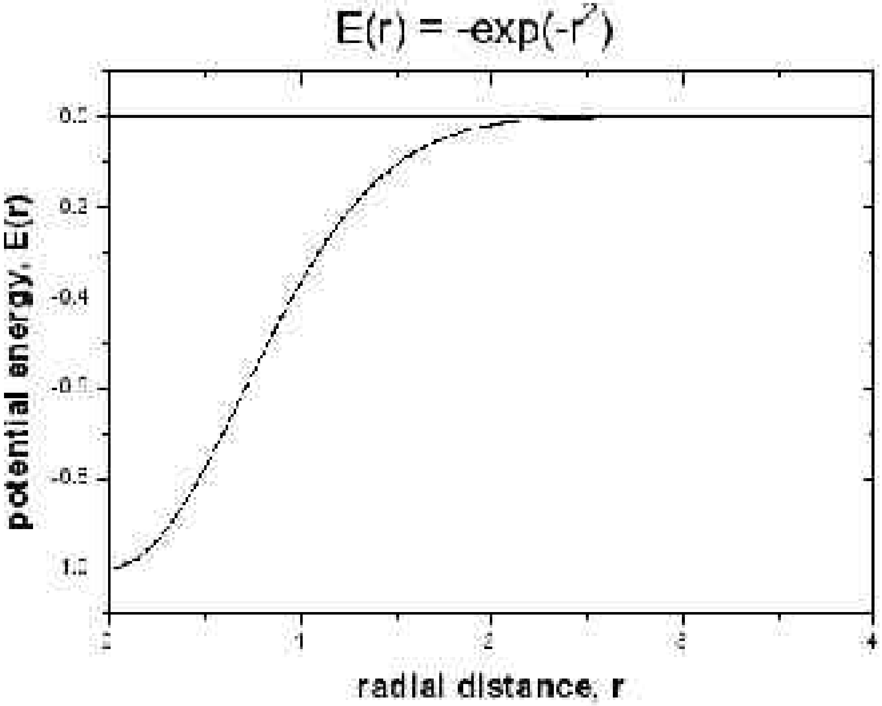
Modulate force at resonant frequency of torsional oscillator

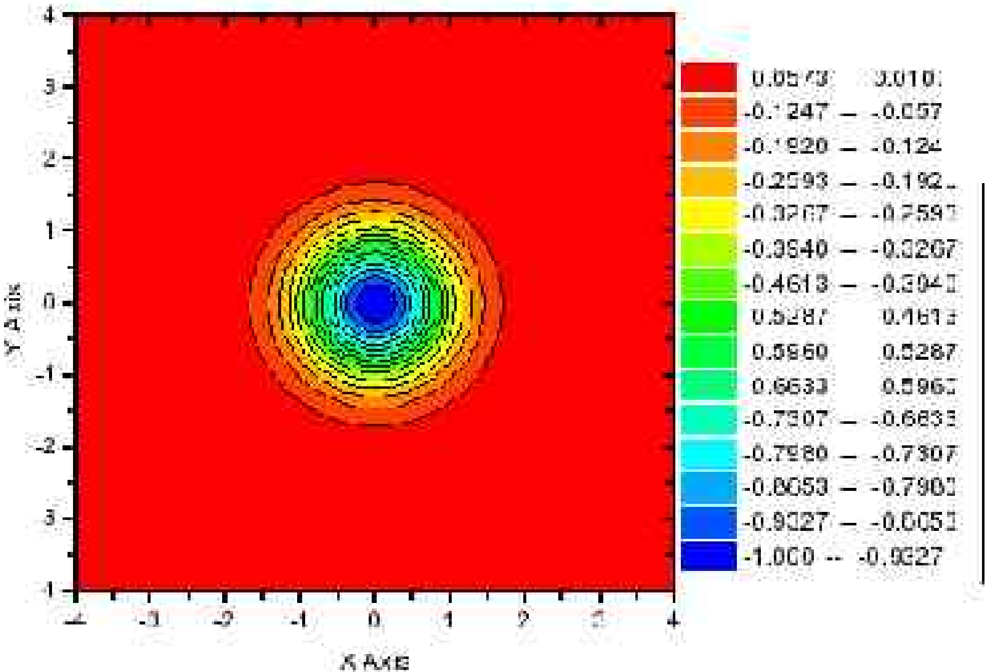


Resonant Amplitude

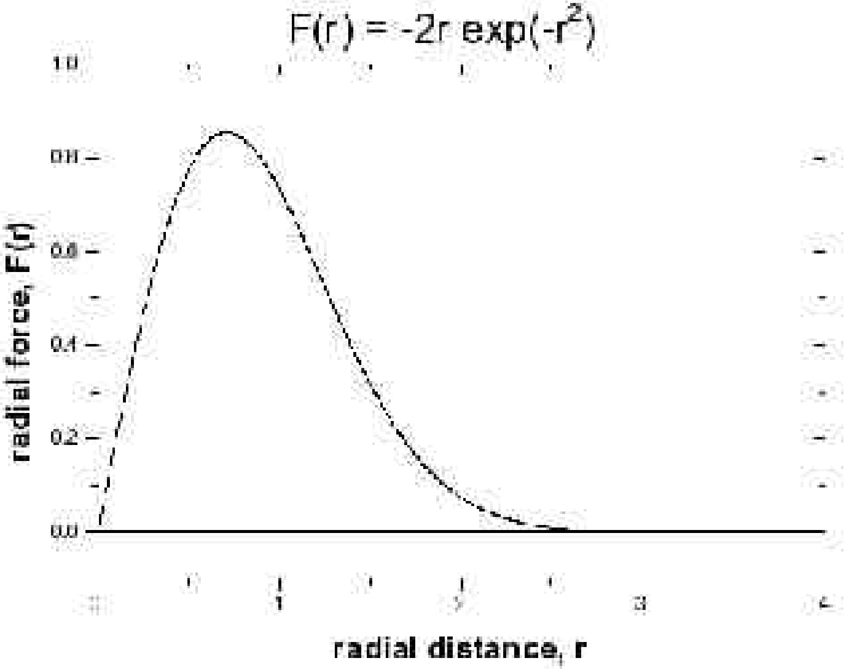


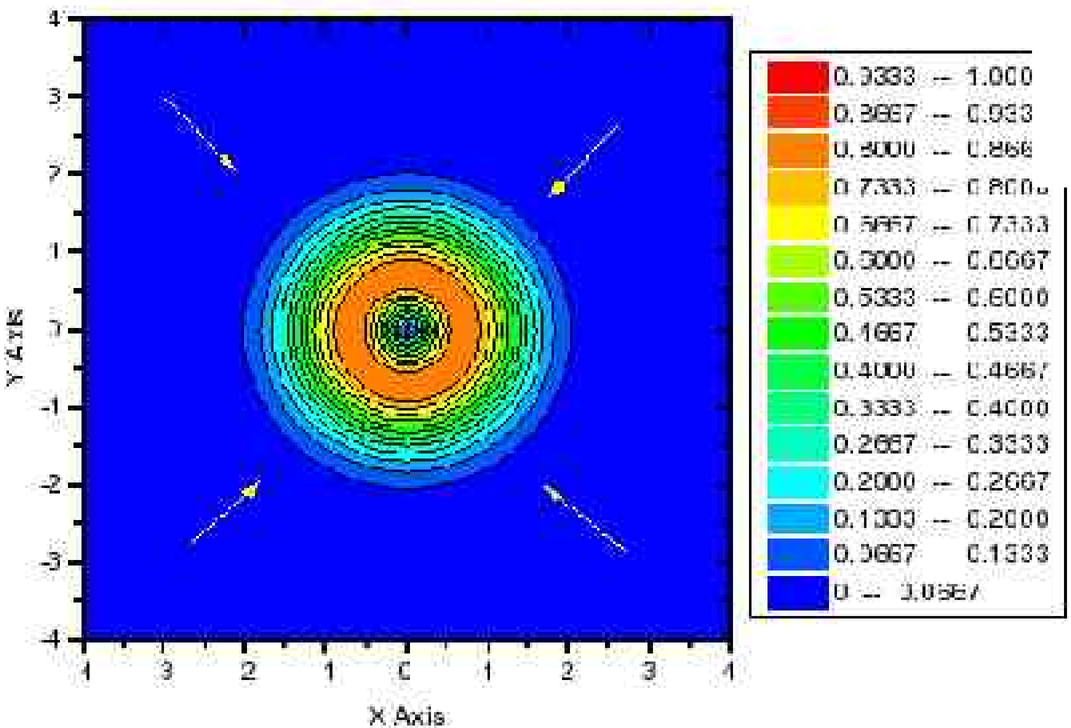
Potential Energy



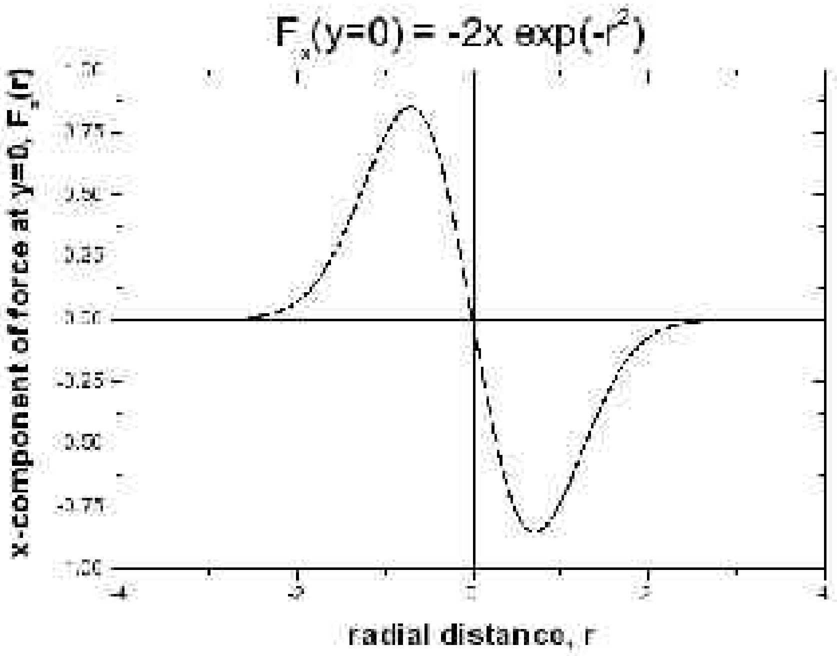


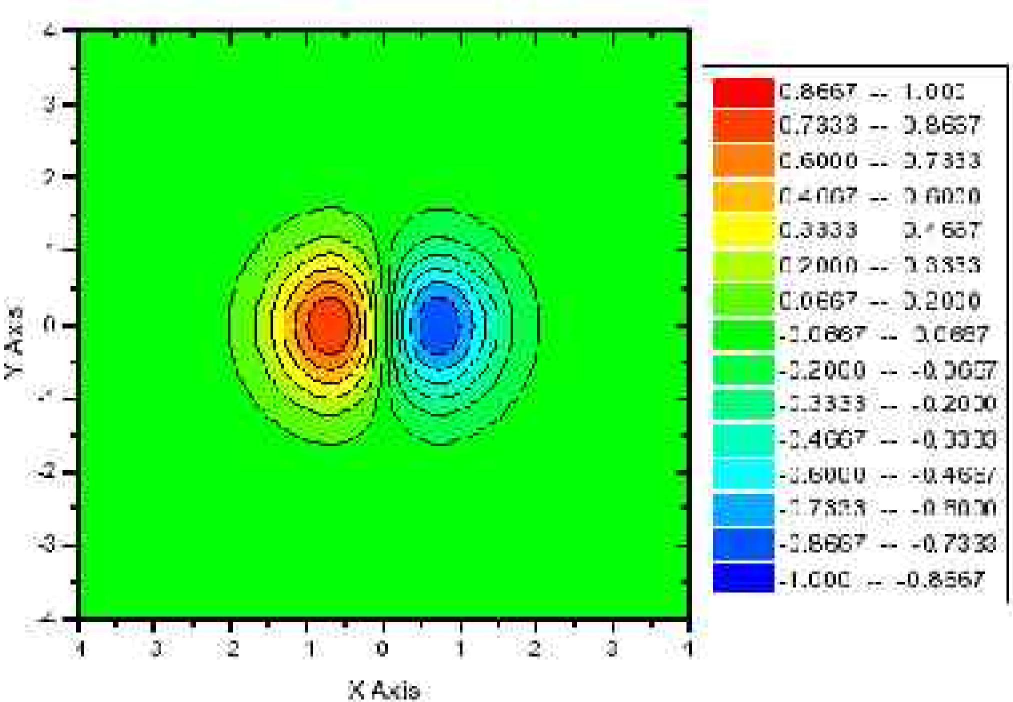
Radial Force



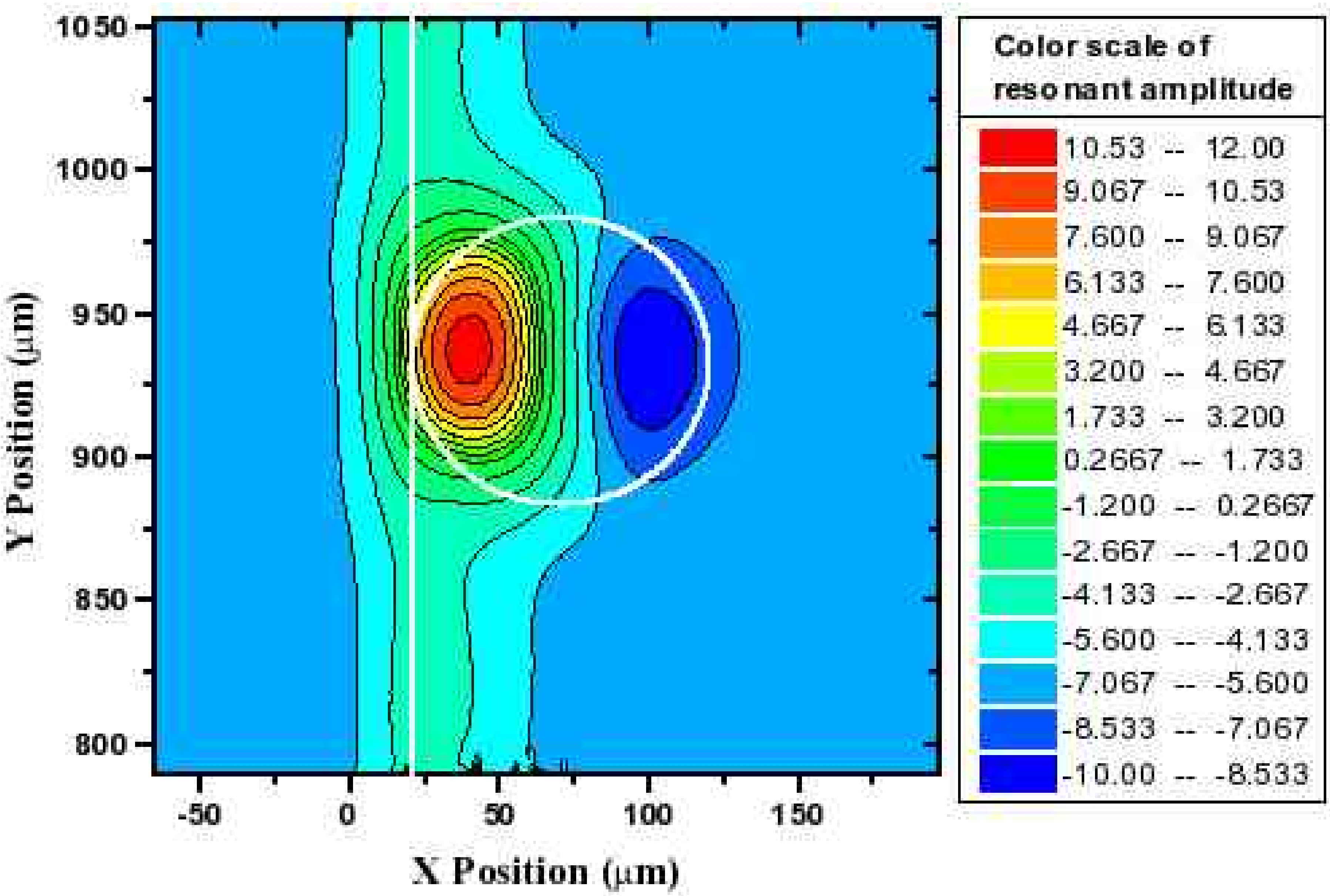


x-component of Force





Resonant Amplitude



Polarization Dependence and Anisotropy Effects

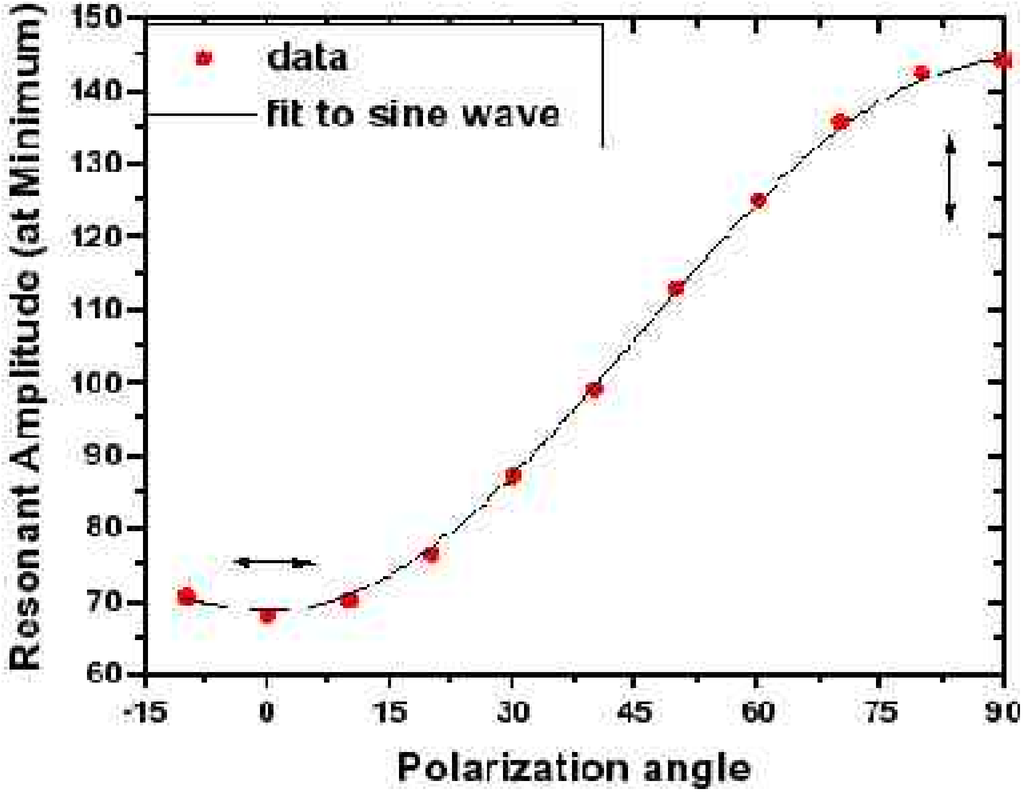
Total force, F, on a piece of polarized dielectric:

$$F = \int (P \cdot \nabla) E \, dV$$

For a *linear and isotropic* dielectric:

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

$$(\mathbf{P} \bullet \nabla)\mathbf{E} = \tfrac{1}{2}\varepsilon_0 \chi \nabla(E^2)$$



If $\mathbf{P} \neq \varepsilon_0 \chi \mathbf{E}$, then force is not radially symmetric

Related to torques observed on asymmetric objects

Quantitative Results

- Thermal time constant ~ 35 ms
  conduction through rods + some radiative coupling
- 4 methods for calibrating optical force: detection electronics, electrical drive, thermal noise of oscillator (equivalent to method used for tweezers), detector noise
- Displacement noise: $x_n = 2.0$ pm/Hz$^{1/2}$ off resonance
- Force noise: $f_n = 6.0$ pN/Hz$^{1/2}$ off resonance
- Equivalent noise: $f_n' = 0.017$ pN/Hz$^{1/2}$ on resonance
- Displacement ~ 4.4 pm at dc, 110 nm at resonance, 3 mW
- Force experimentally observed:
  $F = 0.26$ pN/mW ± many systematic checks
- Force theoretically expected:
  $F \sim 0.06/c = 0.20$ pN/mW ± detailed calculations
- Anisotropy (~3:1), some idea why, interesting in itself

Conclusions

Convincing evidence of radiation pressure on a dielectric sphere:

- numbers are reasonable
- separation of thermal effects from radiation pressure by examining the frequency dependence
- spatial variation is reasonable

See anisotropy/polarization effects in present device

Better S/N by working at resonance (~ 0.017 $\mathrm{pN/Hz}^{1/2}$)

Significant actuation of the MEMS device (110 nm)

With enhancements and optimization ↙ potential for interesting all-optical devices