MEMS and Nanophotonics Integration for Sensor Applications

Dustin W. Carr, Bianca E. N. Keeler, Greg Bogart

Sandia National Laboratories, Albuquerque, NM

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

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Summary

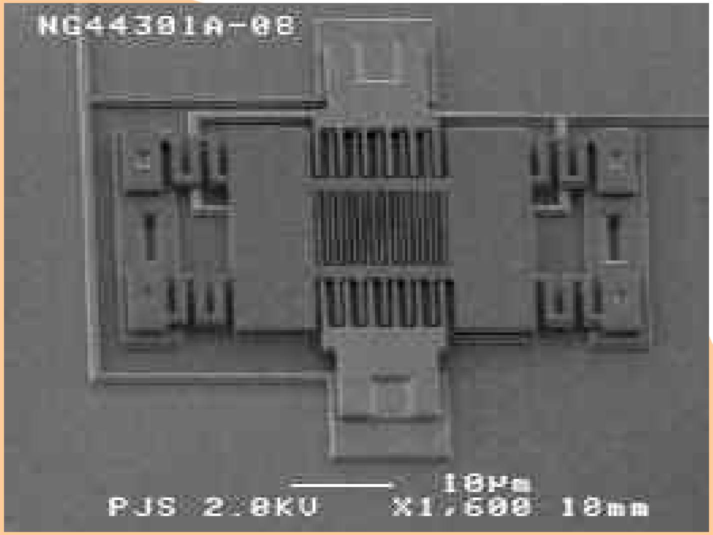
Brief description of Optical NEMS program at Sandia

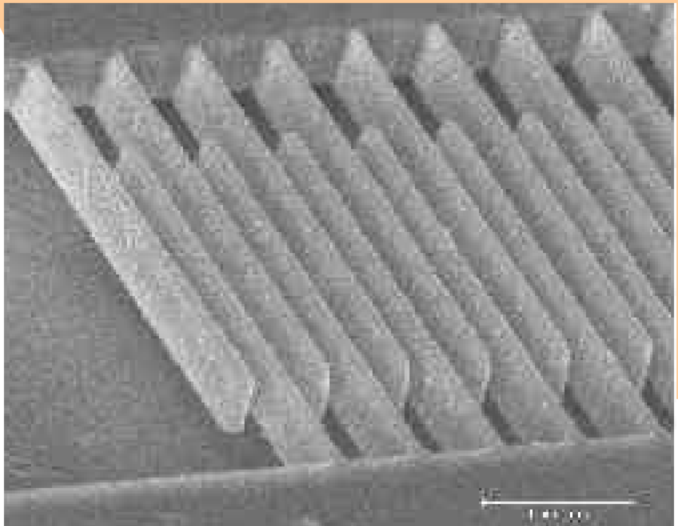
Introduction to Inertial sensor systems and advantages of optical implementations.

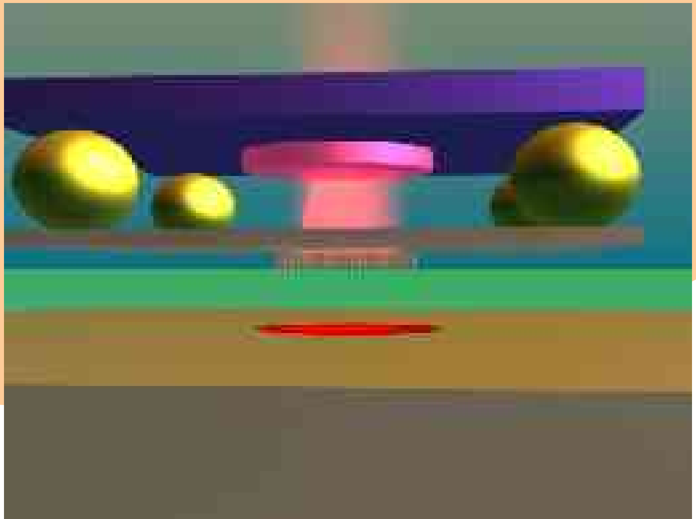
Amorphous diamond grating structures and results

Silicon bi-layer grating structures and results

Work from other groups in this area







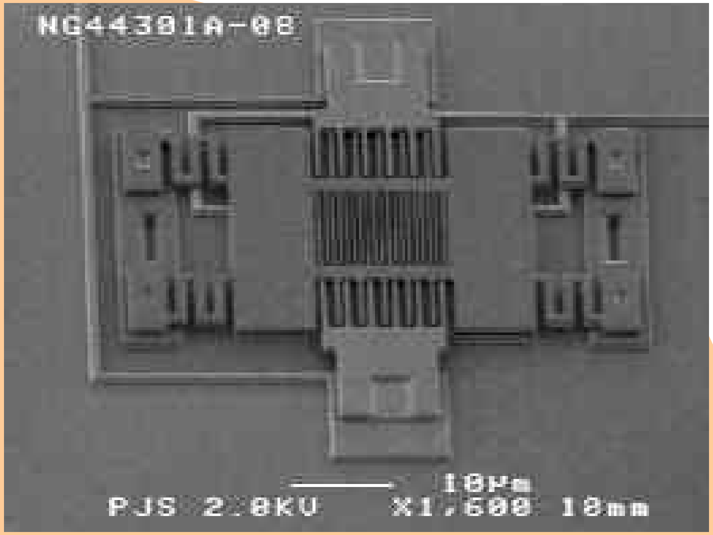
Optical Transducers Technology at Sandia

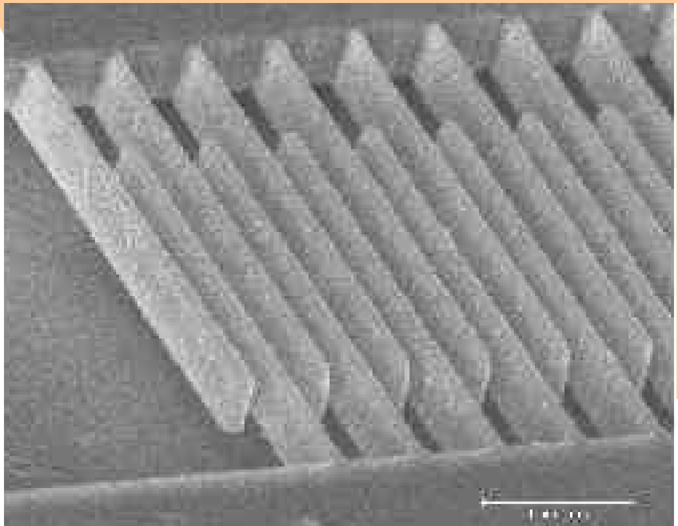
Rapidly growing optical NEMS program at Sandia National Labs, Albuquerque

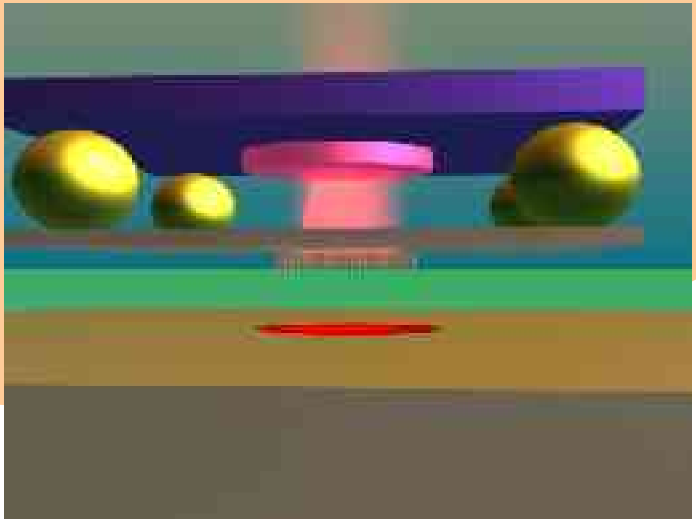
From 0 people,$0 in January 2003

To >5 People ~$2M/year 2005

We take advantage of the dramatic gains in optical MEMS brought about by Telecom investment.







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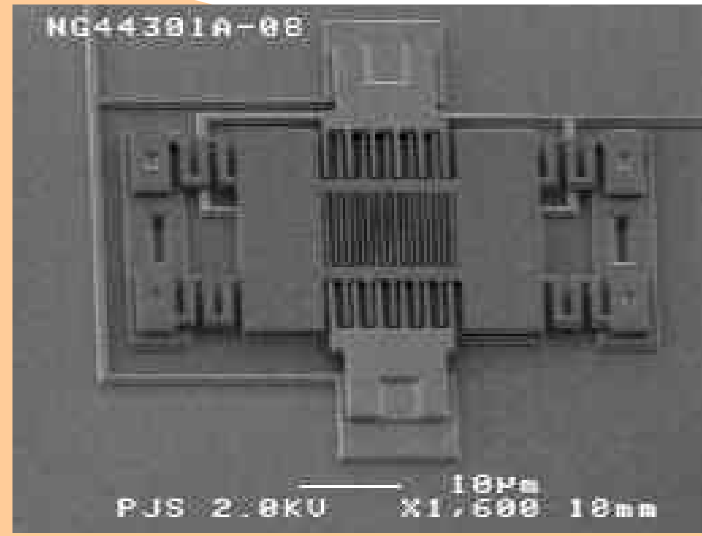
Optical Transducers Technology at Sandia

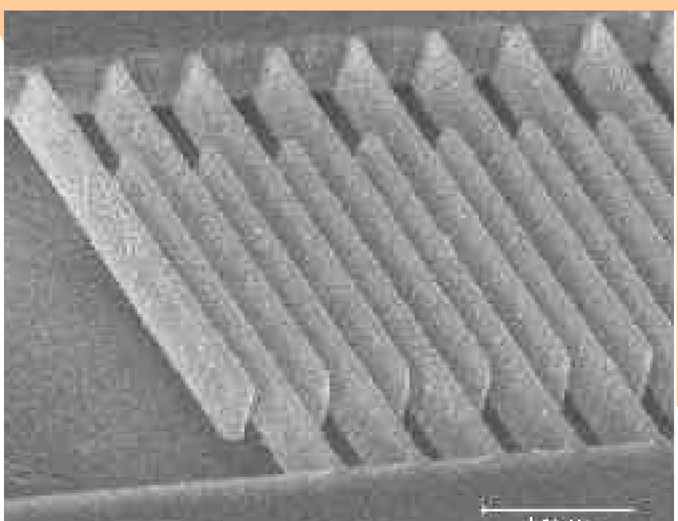
We use this technology to pursue lower hanging fruit.

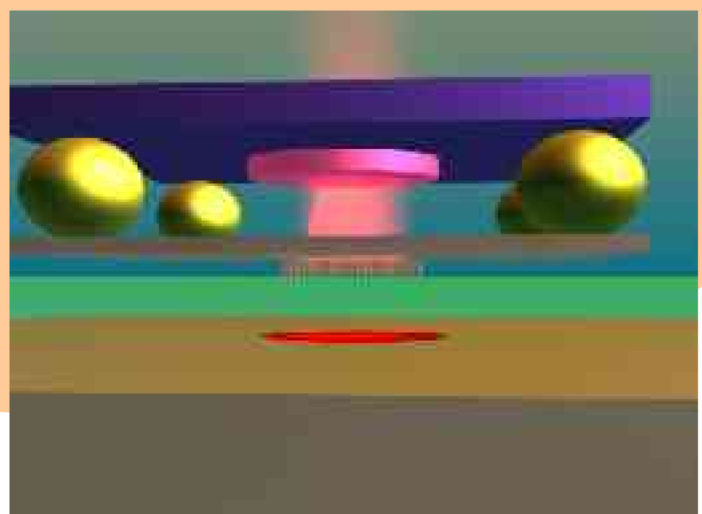
- Inertial sensors for gravimetry, seismology, navigation.
- Flow sensors
- Dynamic strain sensors

Primarily defense oriented, but with many commercial sector applications.

Whitespace opportunities do still exist, high margins, low competition.







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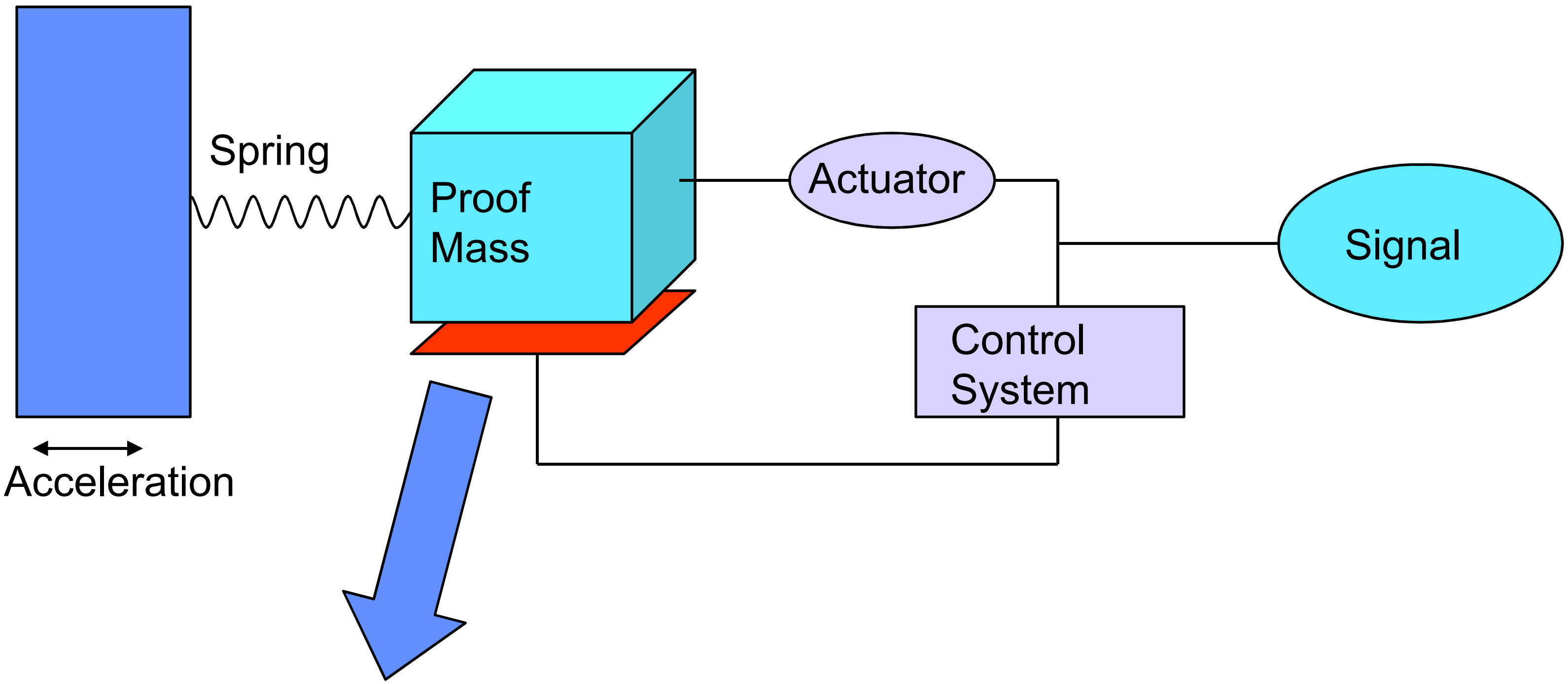
Inertial Sensor Systems



Capacitive Transducer:

Sensing performed through capacitance bridge.

Feedback force applied electrically, Intimately coupled to the sensing mechanism.

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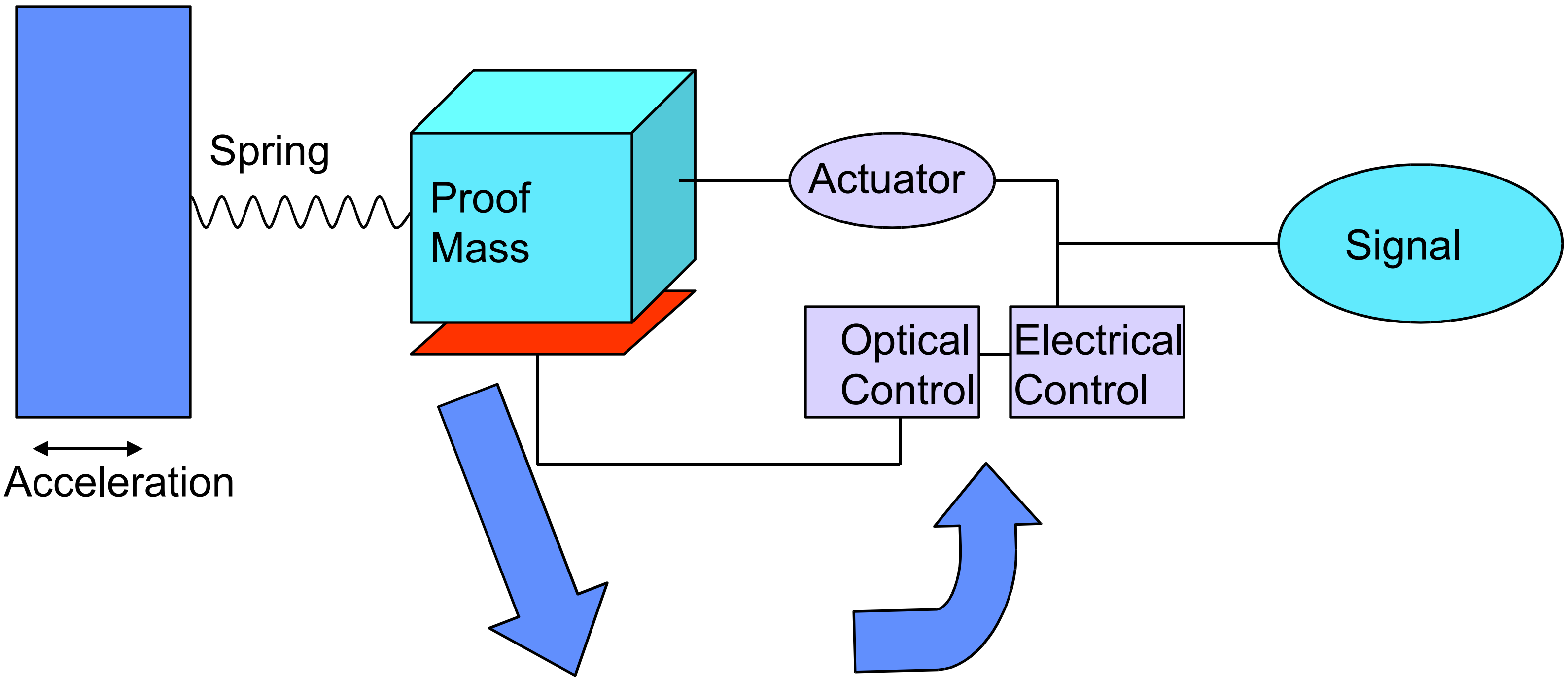
Inertial Sensor Systems



Optical Sensor:

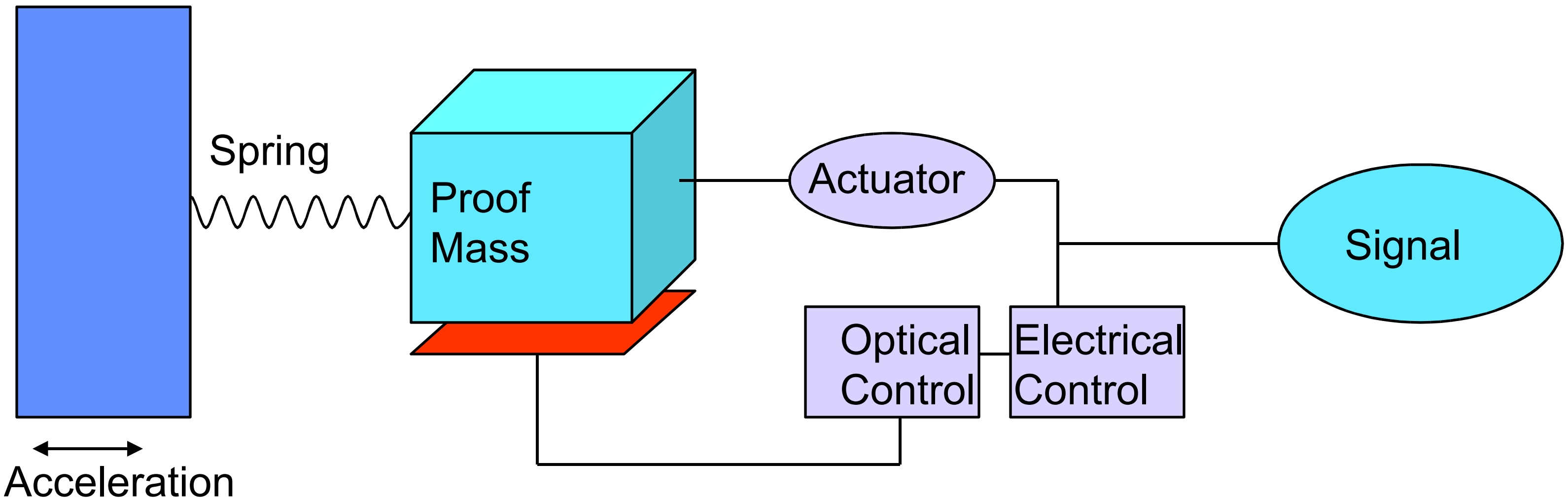
Sensing decoupled from feedback force.

Coherent detection techniques possible in optical domain, enabling noise reduction.

Control system signals generated in optical domain.

More Electrons!

Inertial Sensor Systems



Nano-optics integration techniques enable multi-axis, single chip transducers with remarkable resolution, noise reduction, and simplified control.

Challenges in packaging, but solutions exist thanks to telecom, optical storage market.

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Near-field effects for transducers

- Coupling nanoscale features in an optical near field results in very complex behavior.
- Very slight changes in configuration can result in dramatic changes in optical properties.
- Conventional optical transducers utilize far-field effects:
  - Shutters
  - Long period gratings
    - Period shift
    - Period doubling
- By interacting in the near field, neither the period nor the effective index of refraction must change in order to introduce substantial changes in the optical properties.

Single Layer Deformable Grating

D. W. Carr, J. P. Sullivan, T. A. Friedmann, Opt. Let. **28**, 1636 (2003)

s = center to center spacing of nearest neighbor – variable

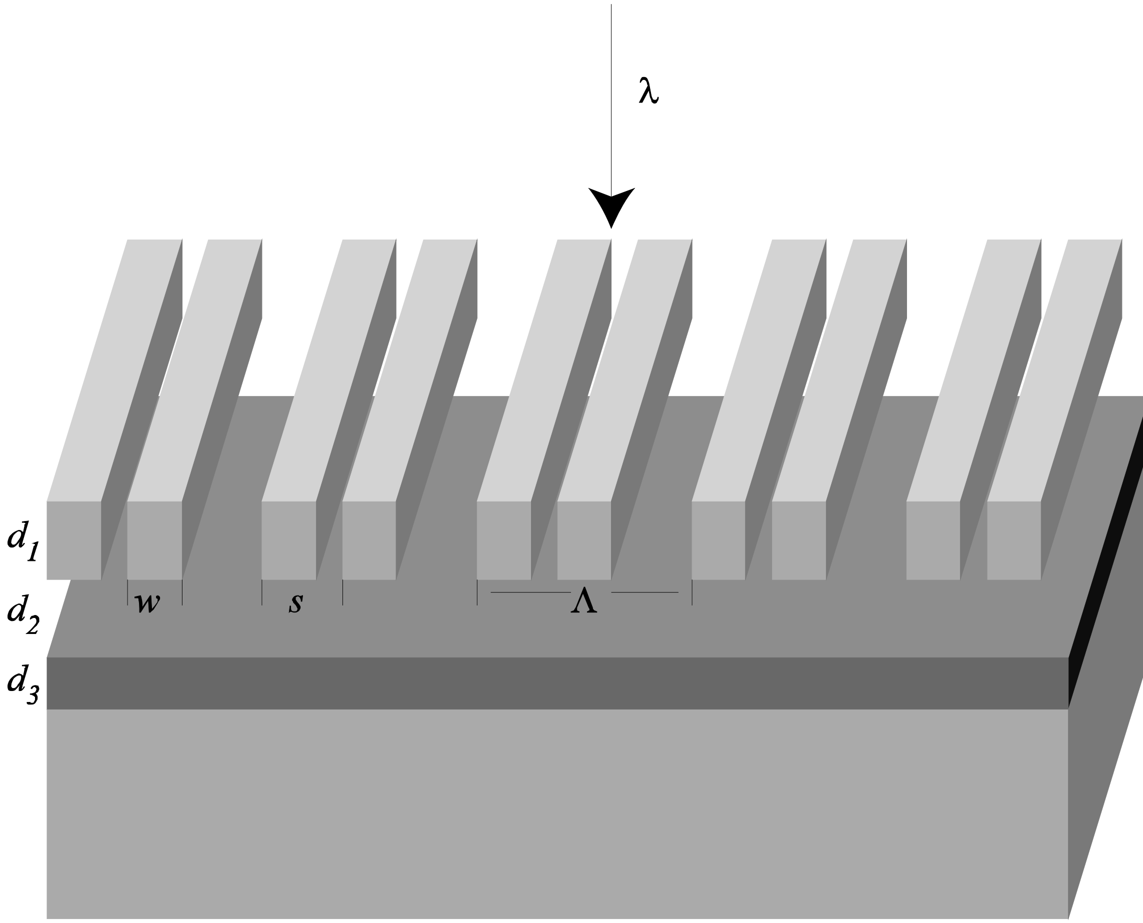
Λ= grating period – 0.6 μm

d_1 = grating thickness, 0.2-0.4 μm

d_2 = air gap, 2.1 μm

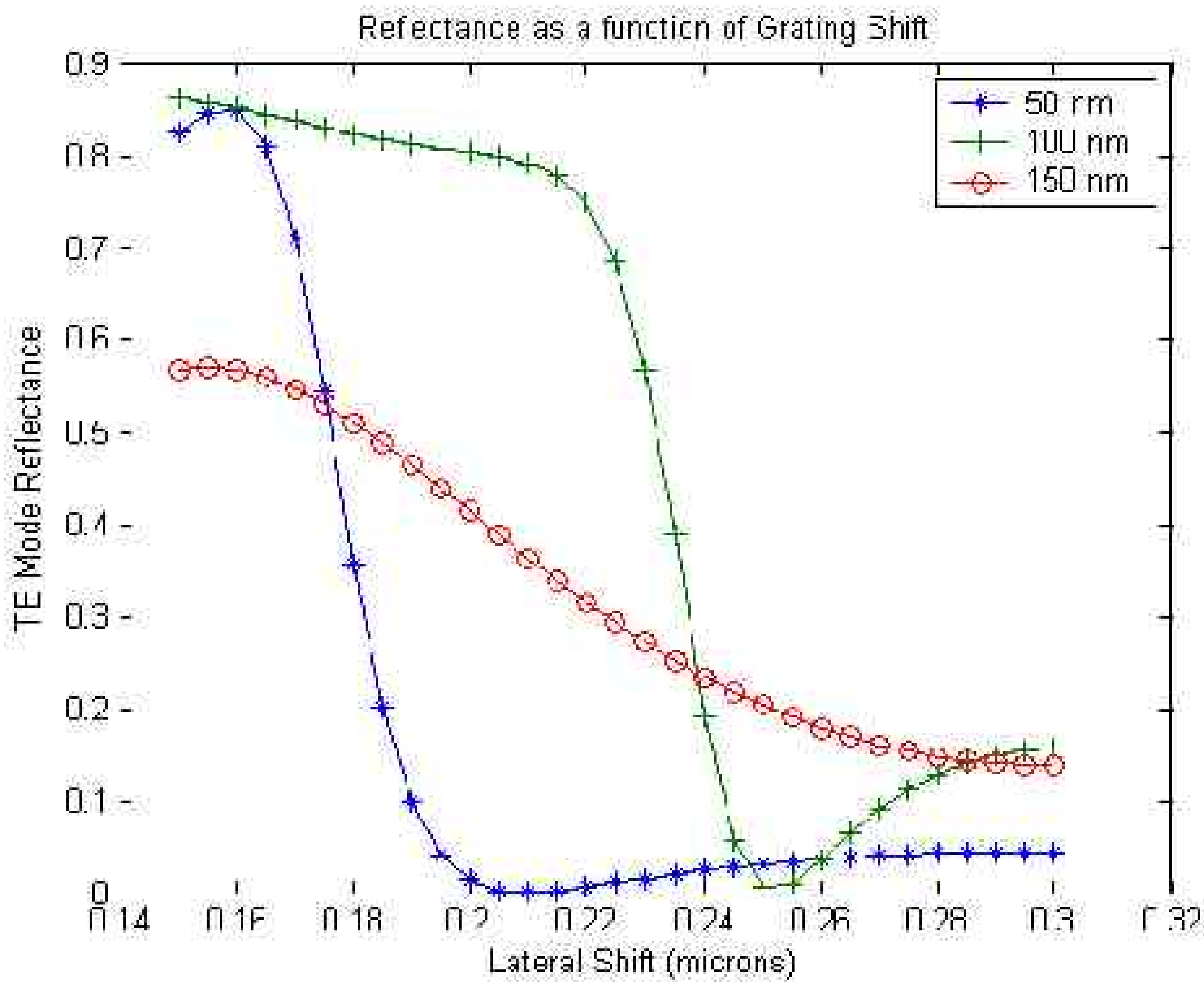
d_3 = ARC

w = beam width, variable, 50-100 nm



Rigorous Coupled Wave Analysis

Prediction of Anomalous Diffraction



Using RCWA, we can calculate the reflectance curve for the laterally deformable gratings.

Maximum slope of reflectance vs. shift can be greater than 0.3 dB/nm. This can result in a noise equivalence below 10 fm/Hz$^{1/2}$ using a typical optical detector.

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Rigorous Coupled Wave Analysis

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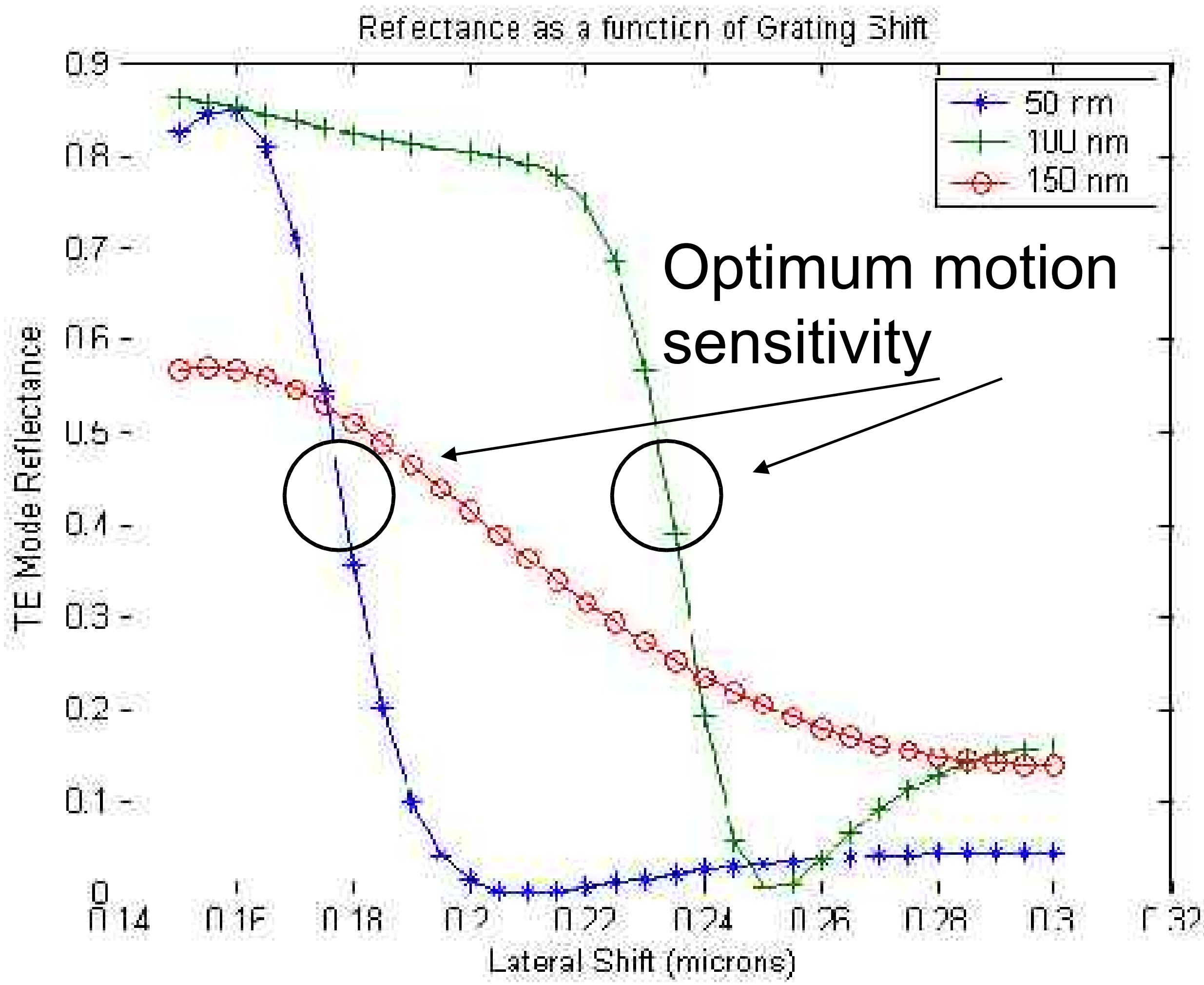

Using RCWA, we can calculate the reflectance curve for the laterally deformable gratings.

Maximum slope of reflectance vs. shift can be as high as 0.3 dB/nm. This can result in a noise equivalence <10 fm/Hz$^{1/2}$ using a typical optical detector.

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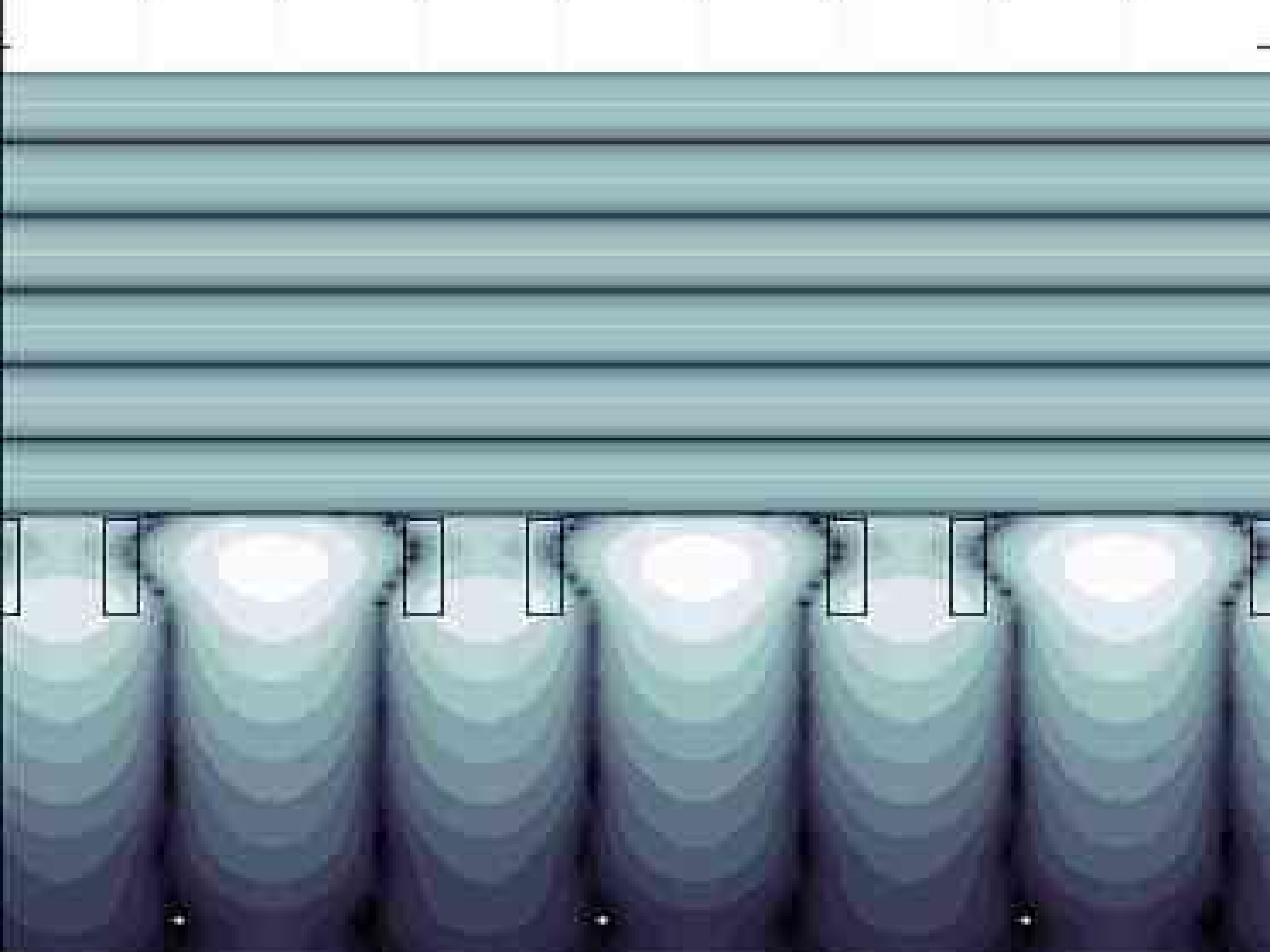
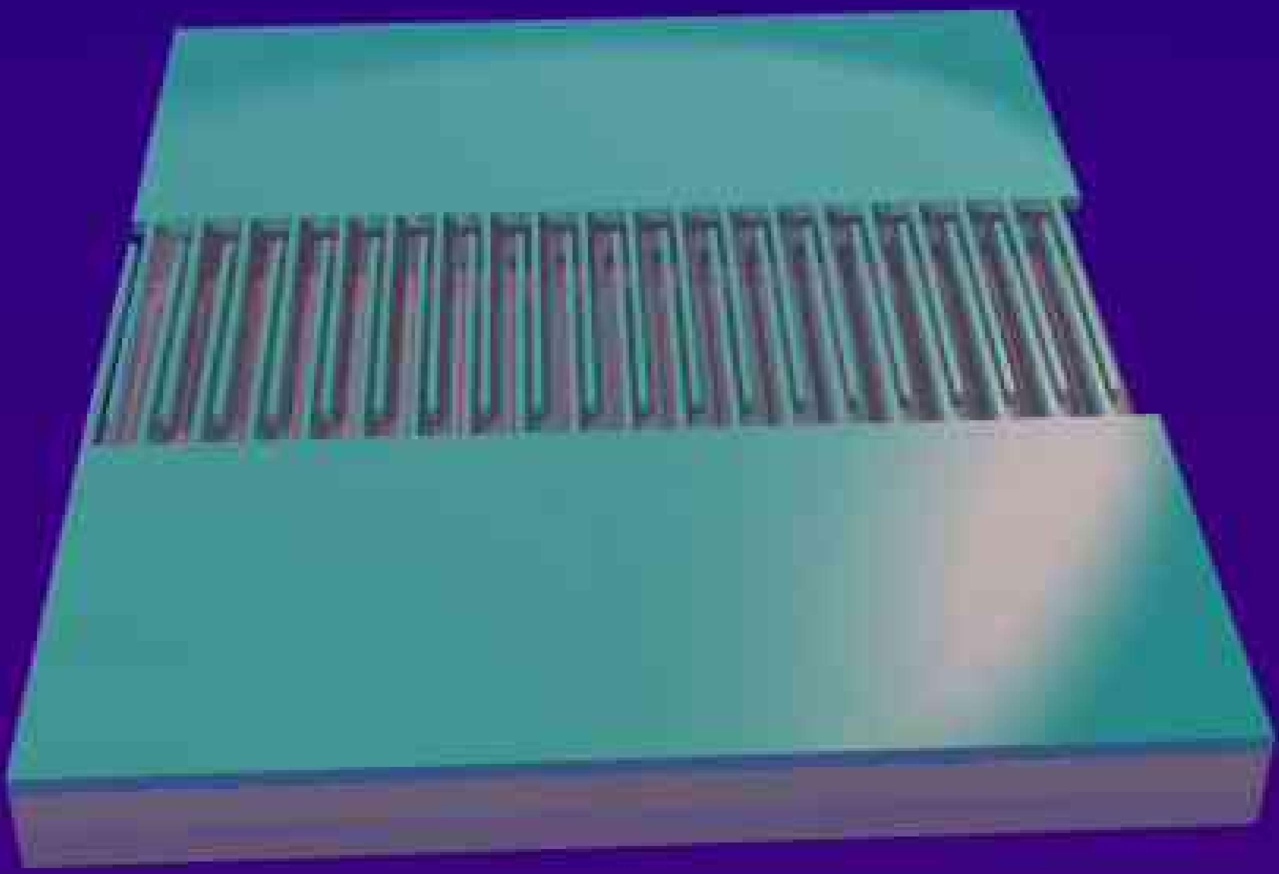
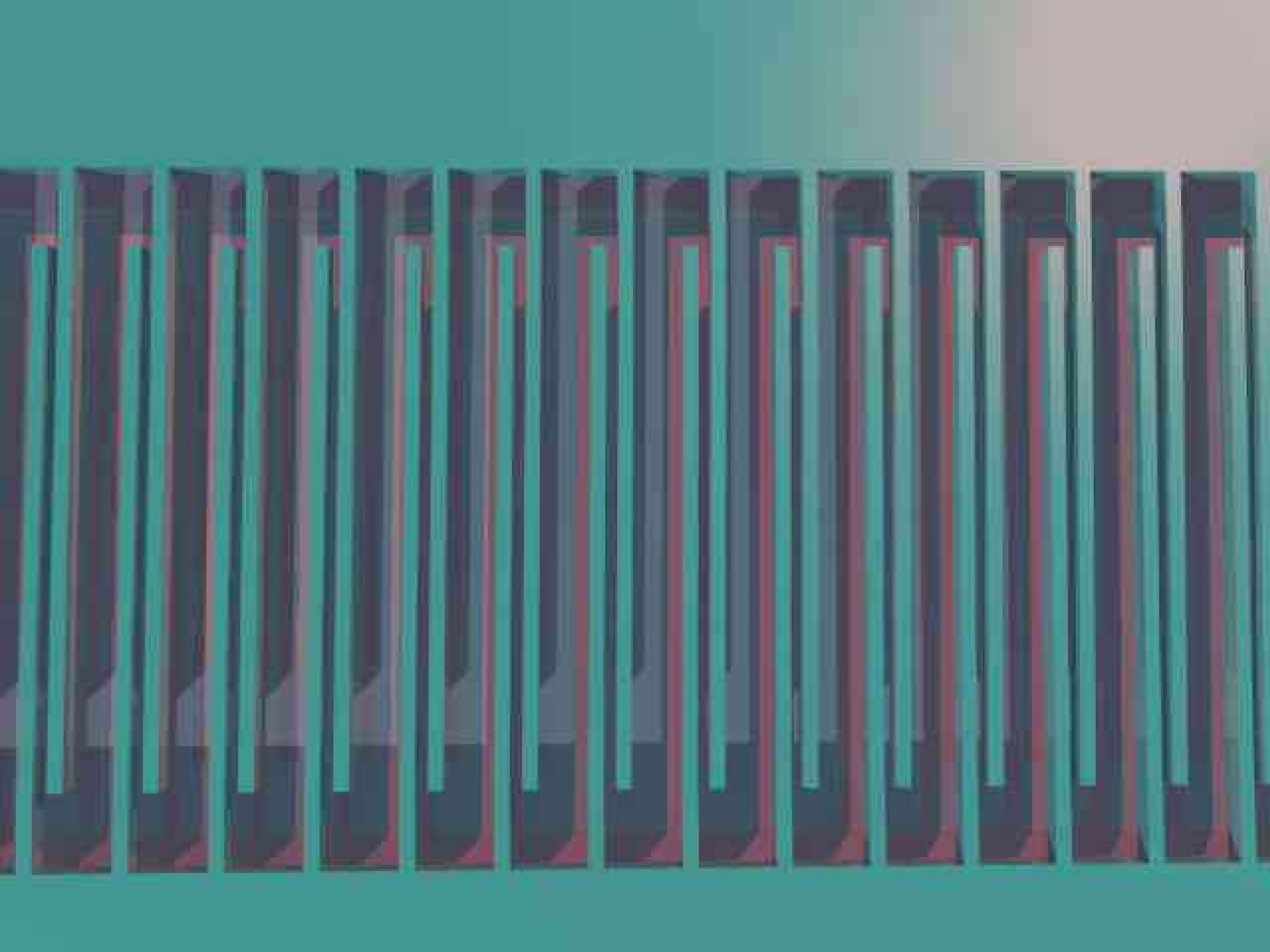
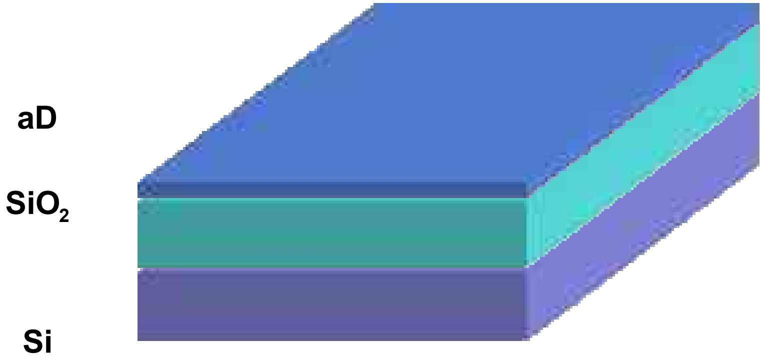




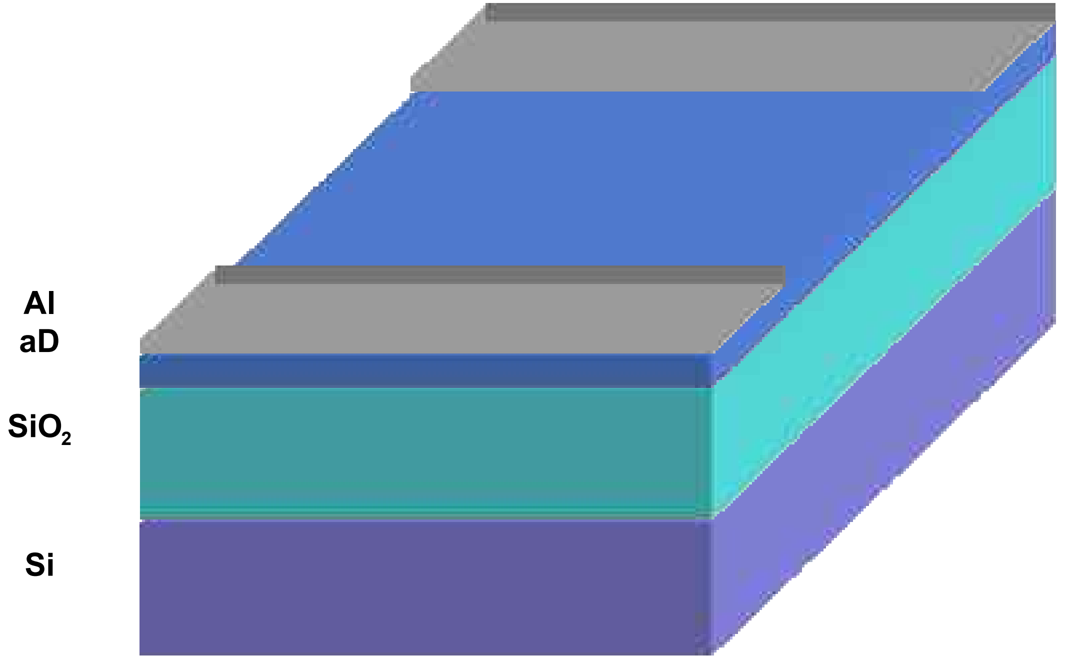


Device fabrication



2 μm SiO_2 and 0.4 μm amorphous diamond are deposited on Si substrate

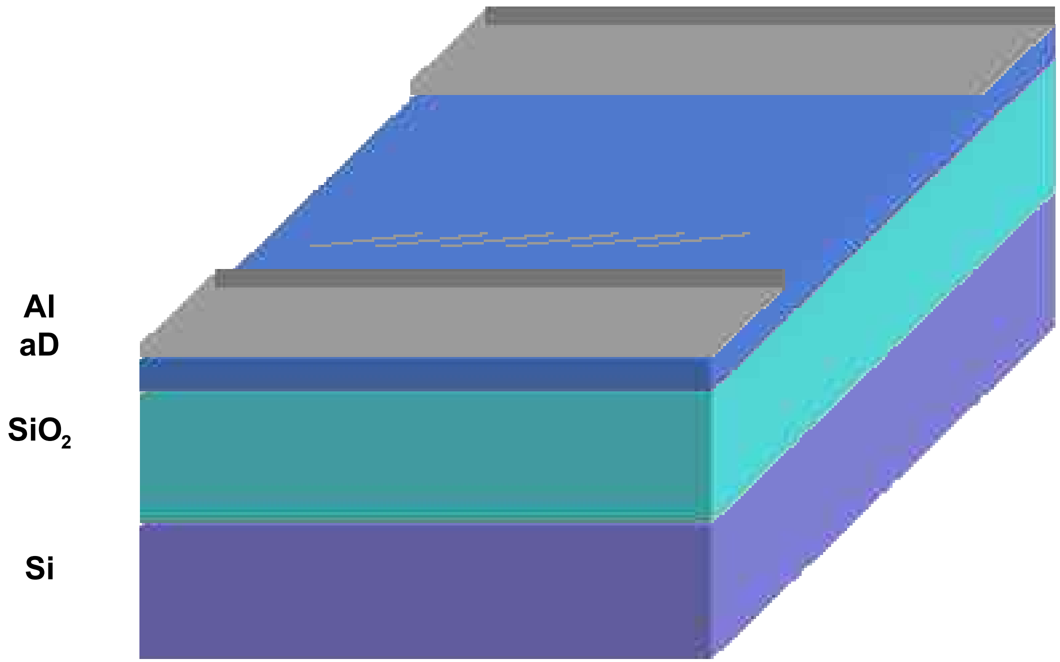
Device fabrication



Aluminum contact pads are patterned using photolithography

Contact pads are 320 µm x 720 µm

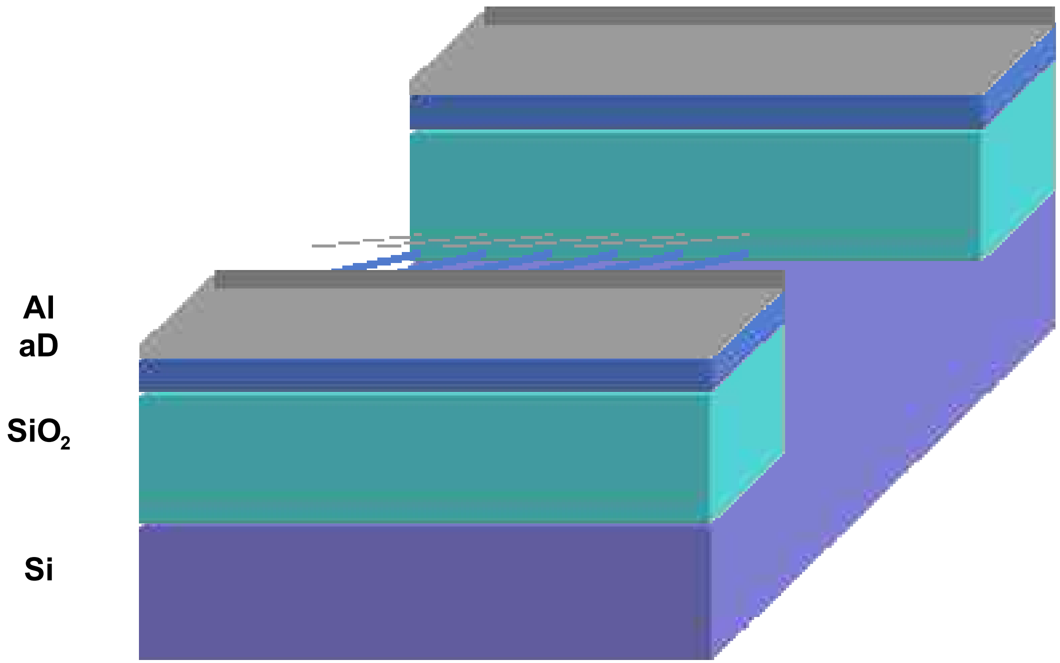
Device fabrication



The grating structures are e-beam written in aluminum

Beams are 50 or 100 nm wide

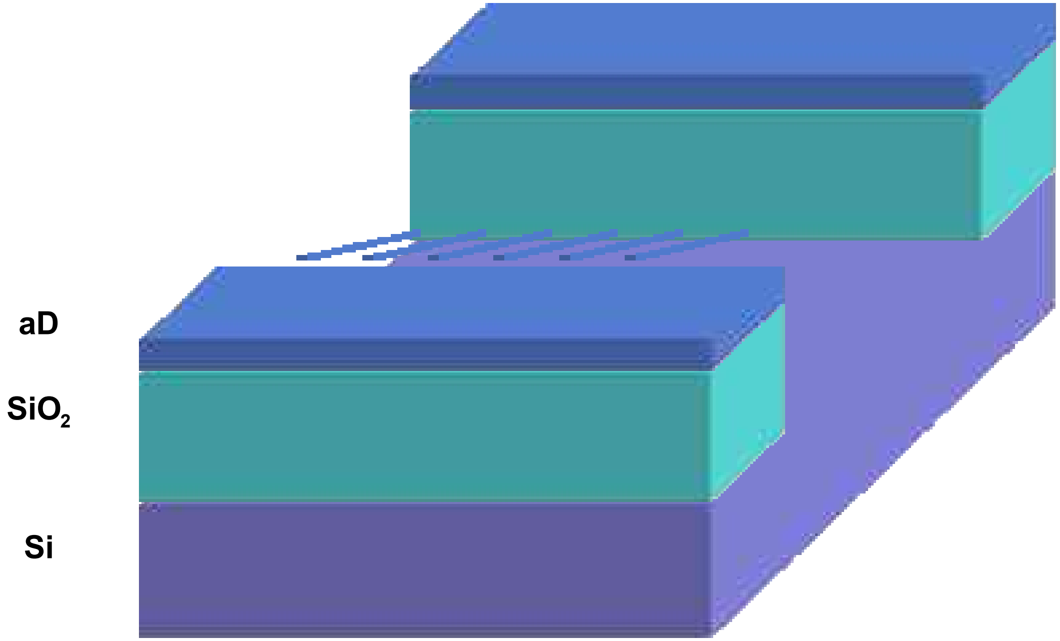
Device fabrication



The aluminum is used as a mask to etch the aD and SiO2

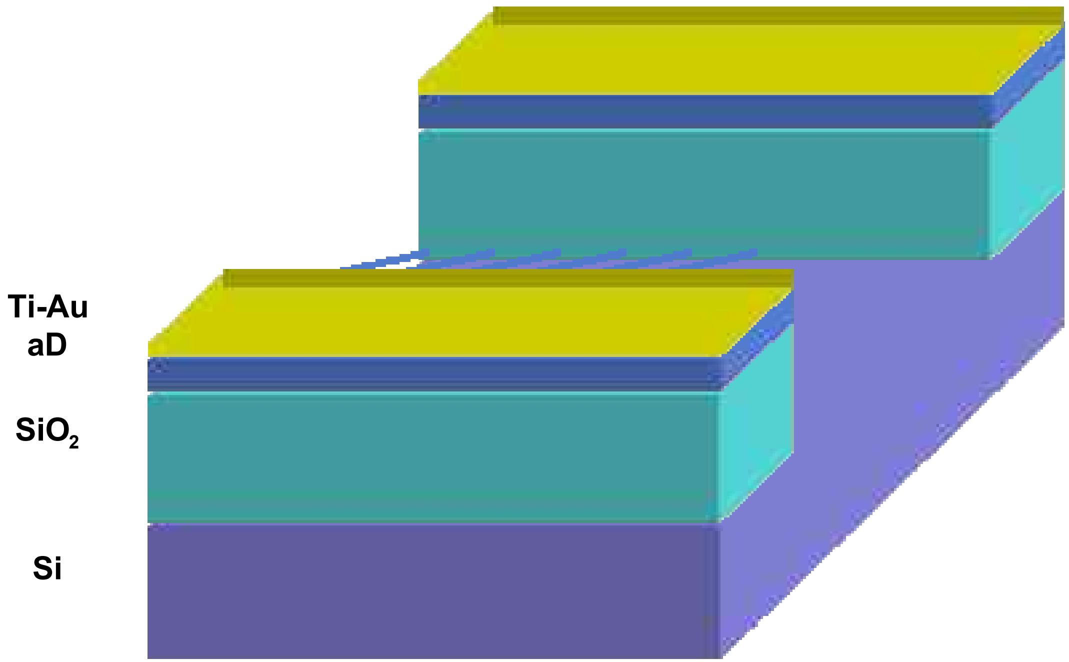
Beams are released

Device fabrication



The remaining aluminum is removed

Device fabrication

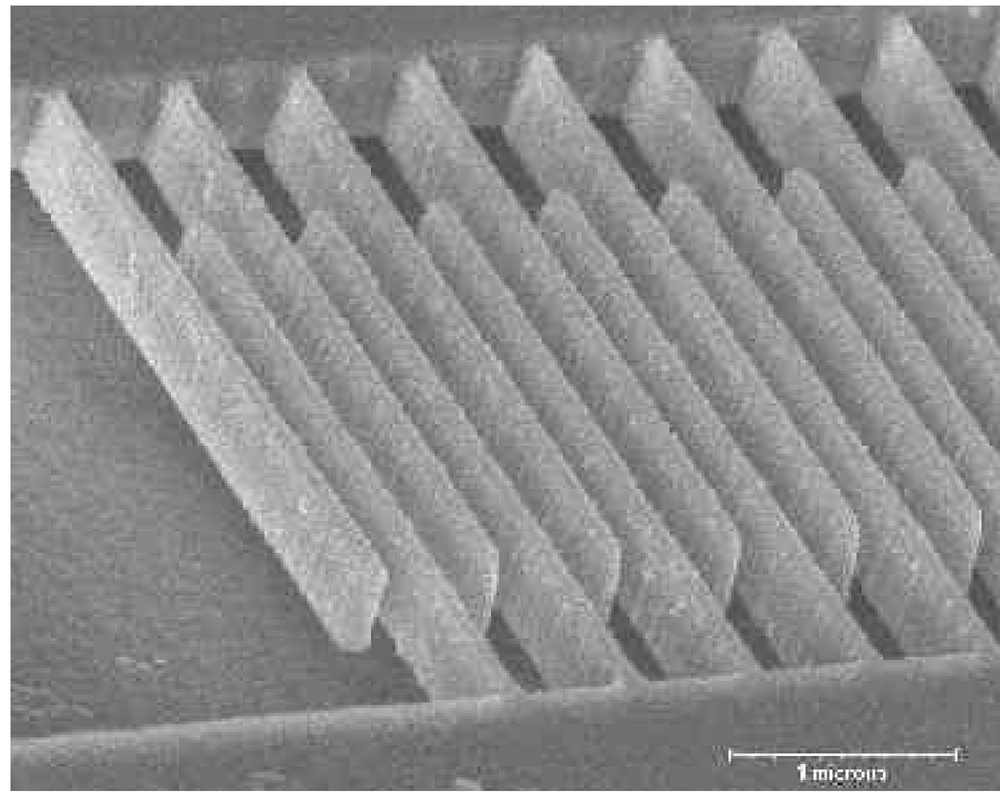


The contact pads are metallized withtitanium-gold

Diamond NEMS Grating

B. E. N. Keeler, D. W. Carr, J. P. Sullivan, T. A. Friedmann, J. R. Wendt, Optics Letters, June 1, 2004.

- **Fabrication of grating in amorphous diamond.**
- **Amorphous diamond material ideal for many mems/NEMS applications (high strength, low density,hydrophobic).**
- **Optical design optimized by RCWA**



Typical grating measured in this work. Beam width is 50 nm, length is 3.2 microns. The total period is 600 nm, and the nearest neighbor spacing is 230 nm.

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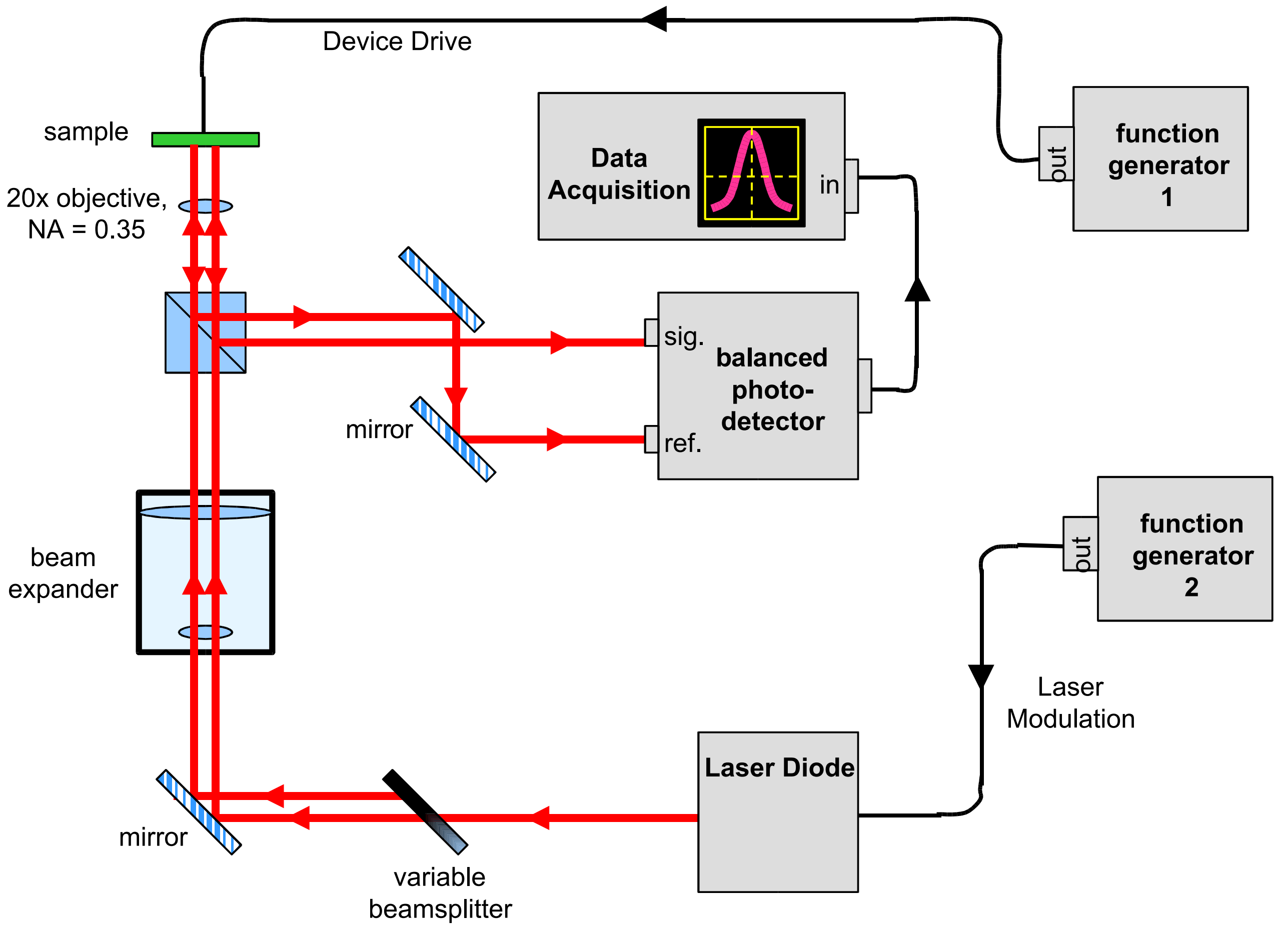
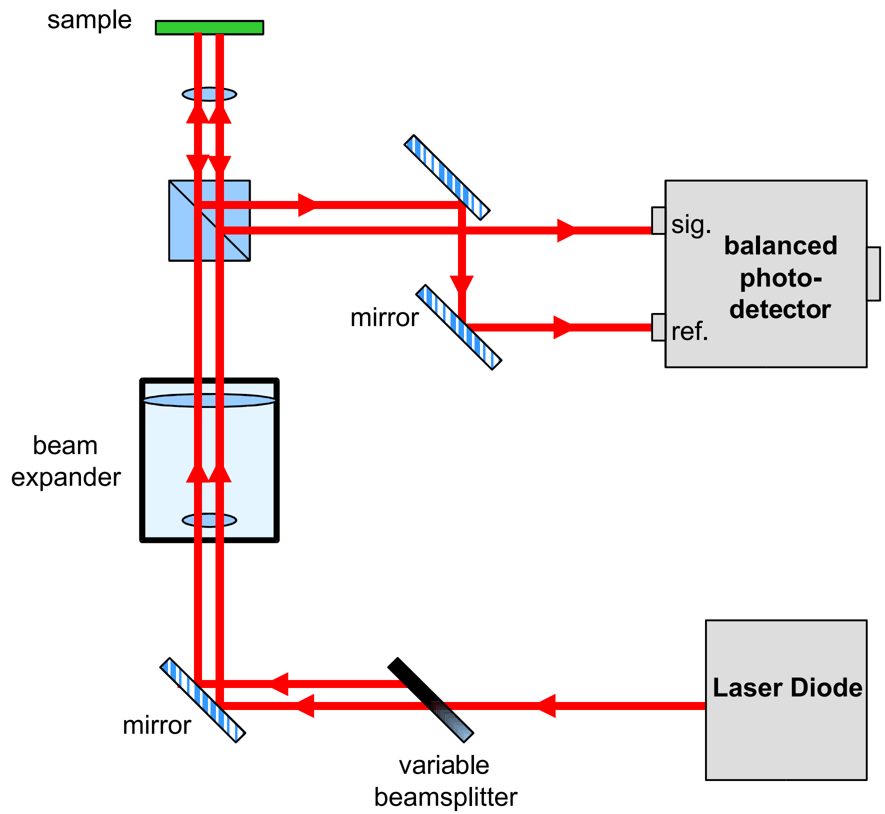
Displacement sensing



Displacement sensing



All of these components exist within CD-ROM read head, <1 cm^3, <$10

Integrated Nano-optics
Comparison to CD-ROM Technology

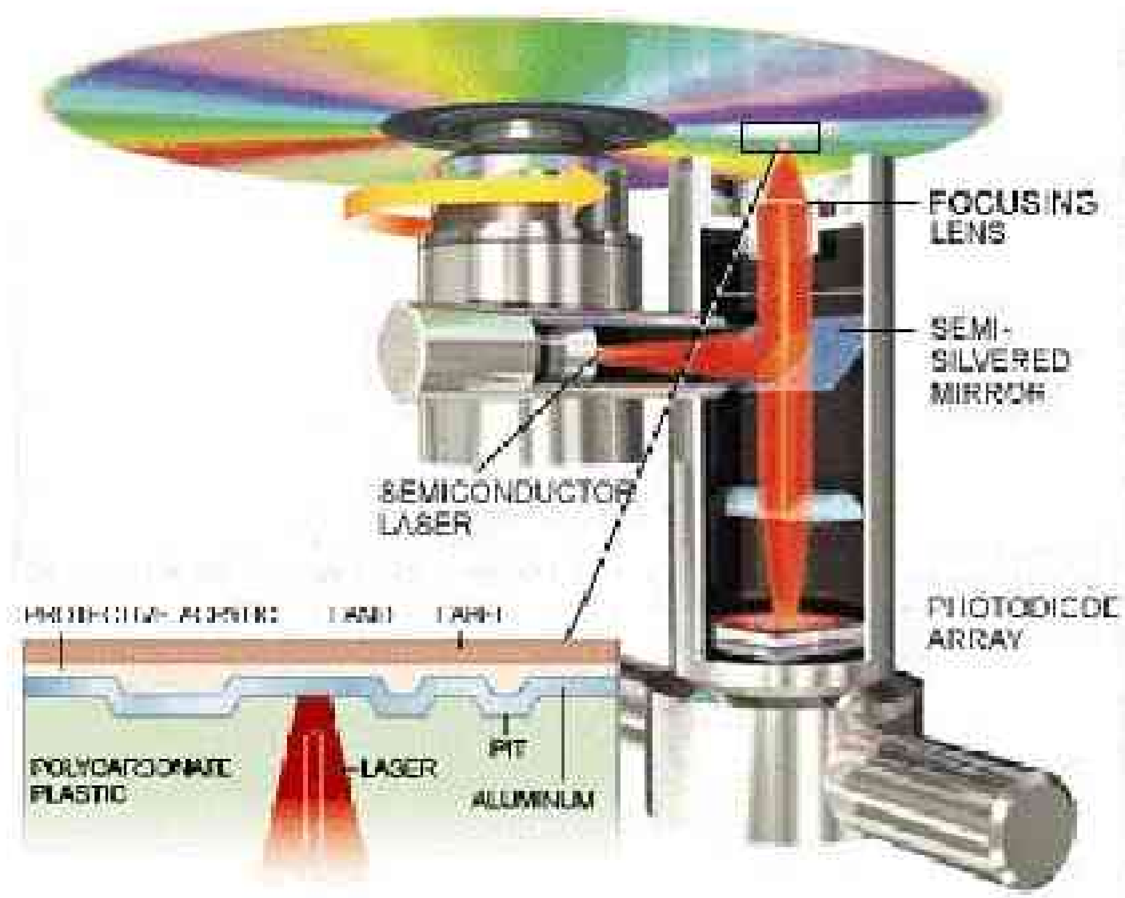
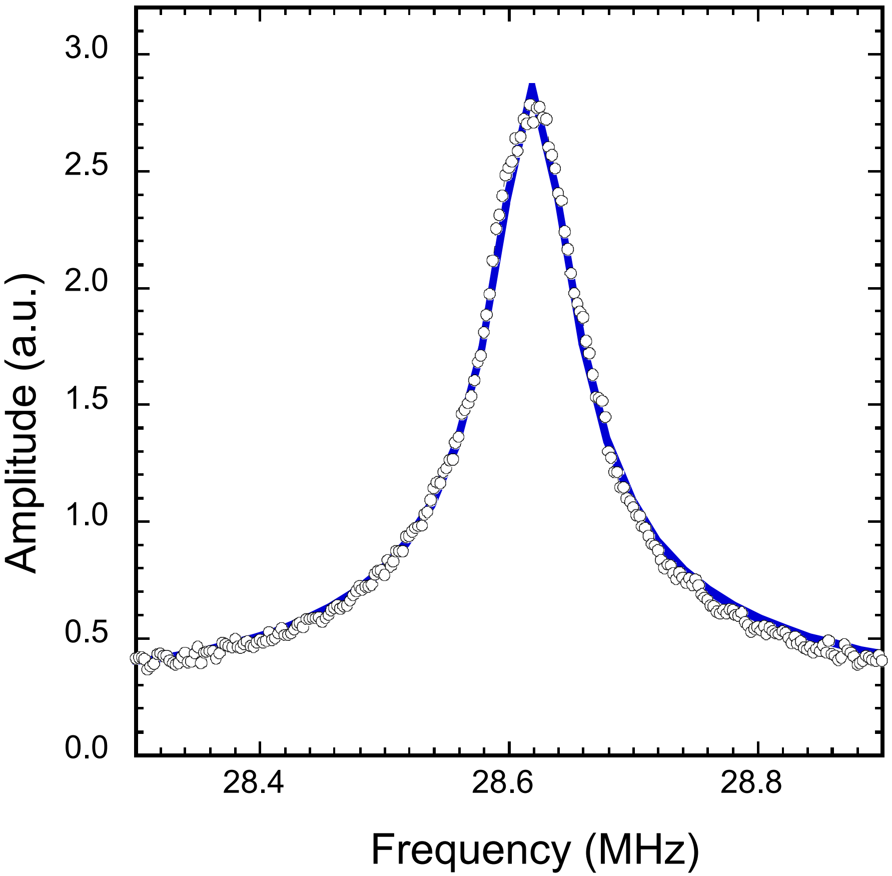


Image from http://www.ex.ac.uk/~mmaziz/soe2142/soe2142_notes_optical.pdf

Experimental results 1 - frequency



Fundamental resonance frequency:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{Ew^2}{12\rho}}\left(\frac{1.875}{L}\right)^2$$

E = 670 GPa (Young's modulus)

ρ = 2900 kg/m^3 (density)

w = 50-100 nm (beam width)

L = 1-8 μm (beam length)

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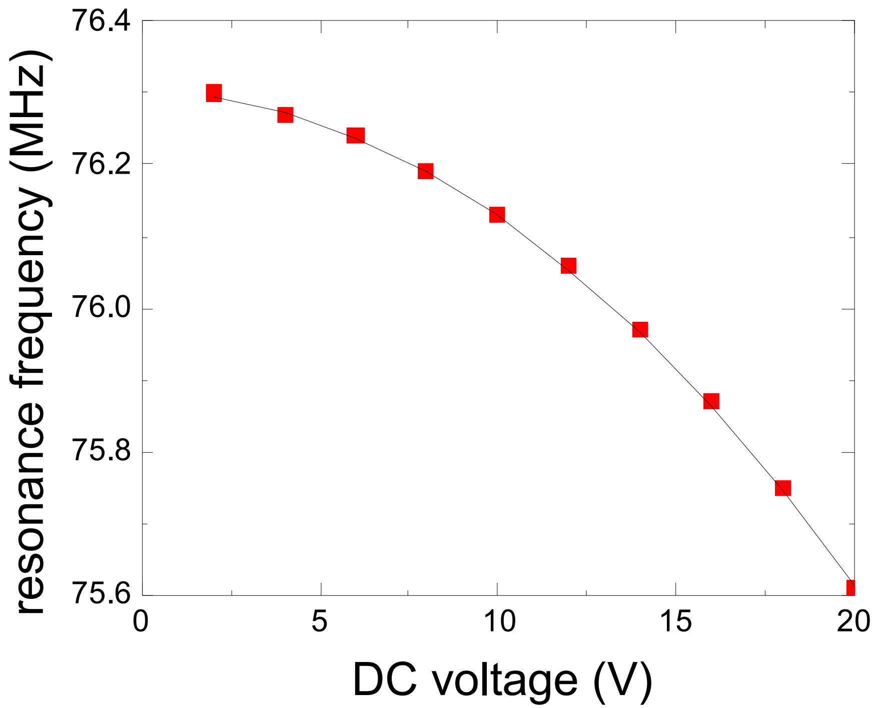
Experimental results 2 – frequency shift



Resonance frequency shift:

$$f_r = \sqrt{f_0^2 - \frac{\varepsilon}{4\pi} \quad \alpha \quad \frac{}{d_0^3} V_{dc}^2}$$

Using simple electrostatic model

A = overlap area

m_{eff} = effective modal mass

d_0 = initial beam separation

V_{dc} = applied dc voltage

α = fitting parameter

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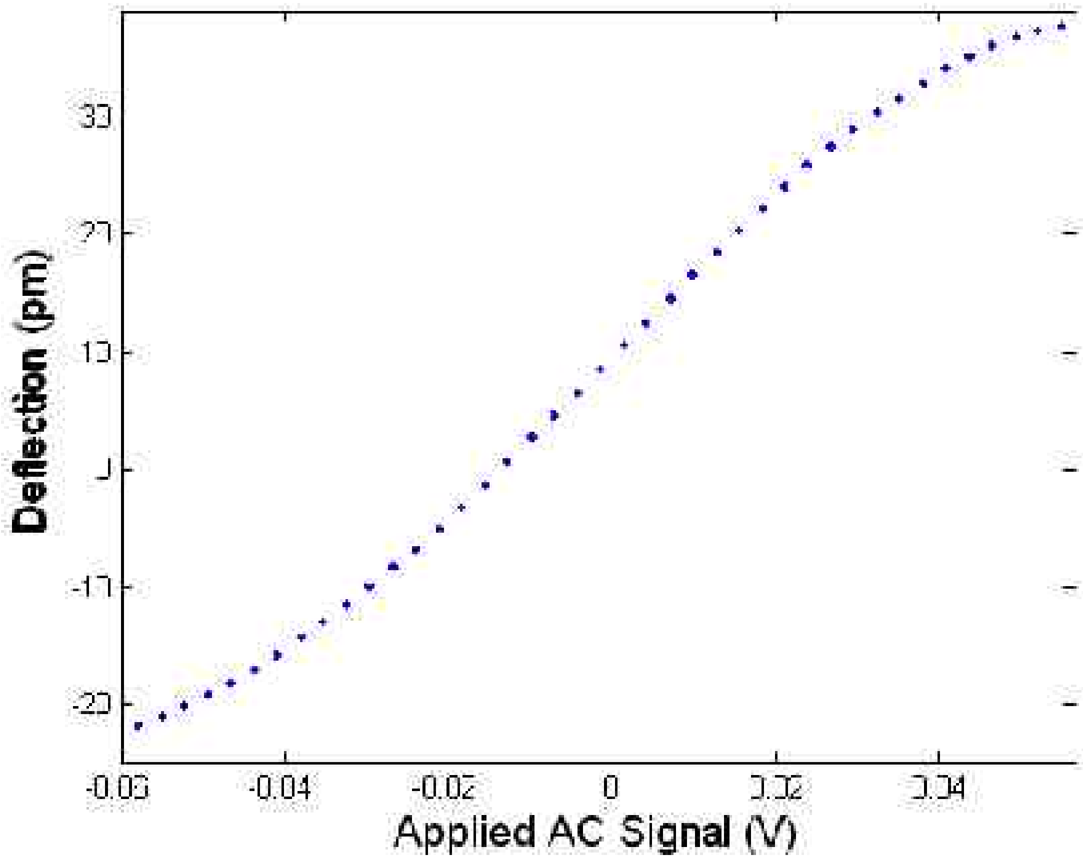
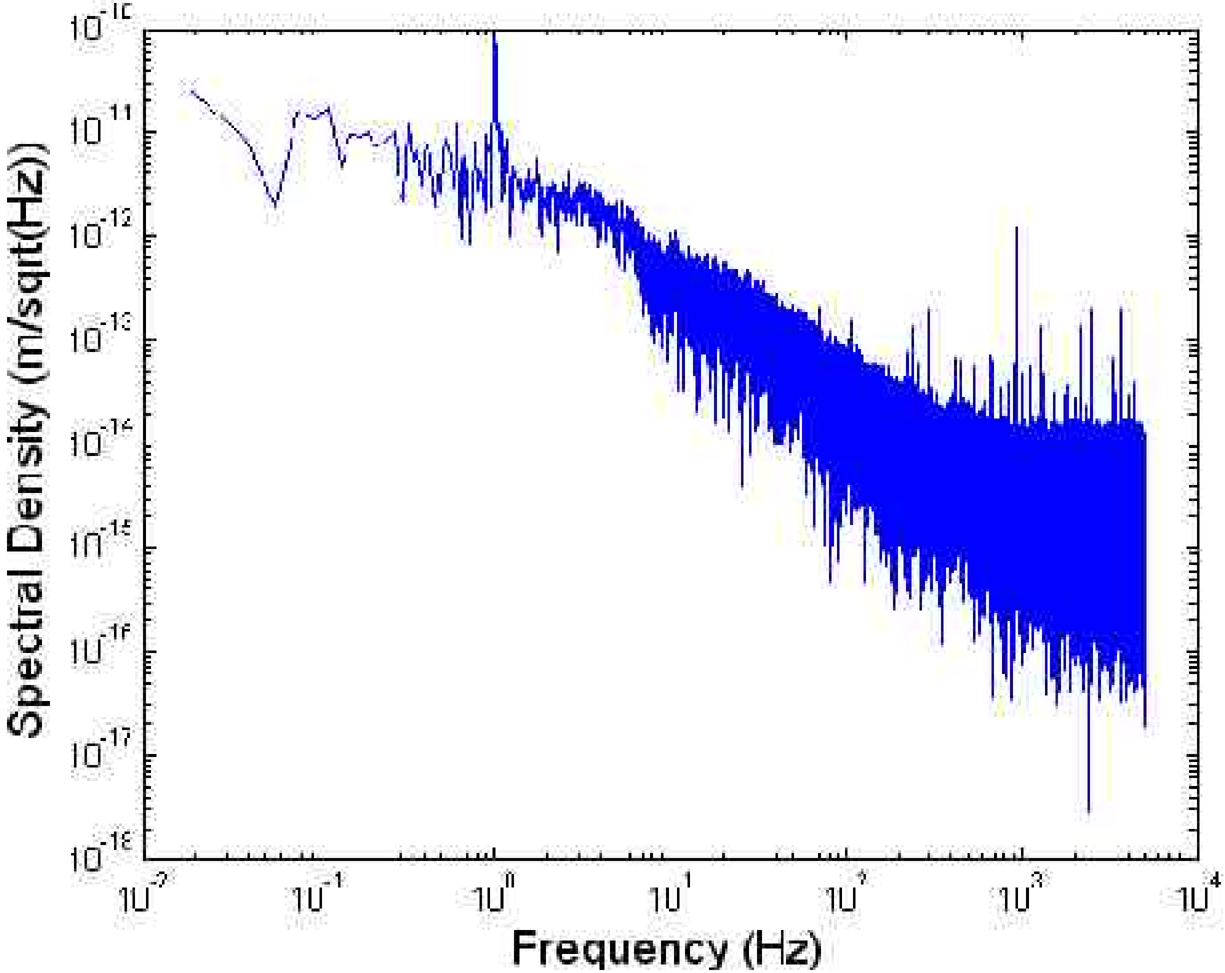
Low Frequency Measurements



Spectral Density

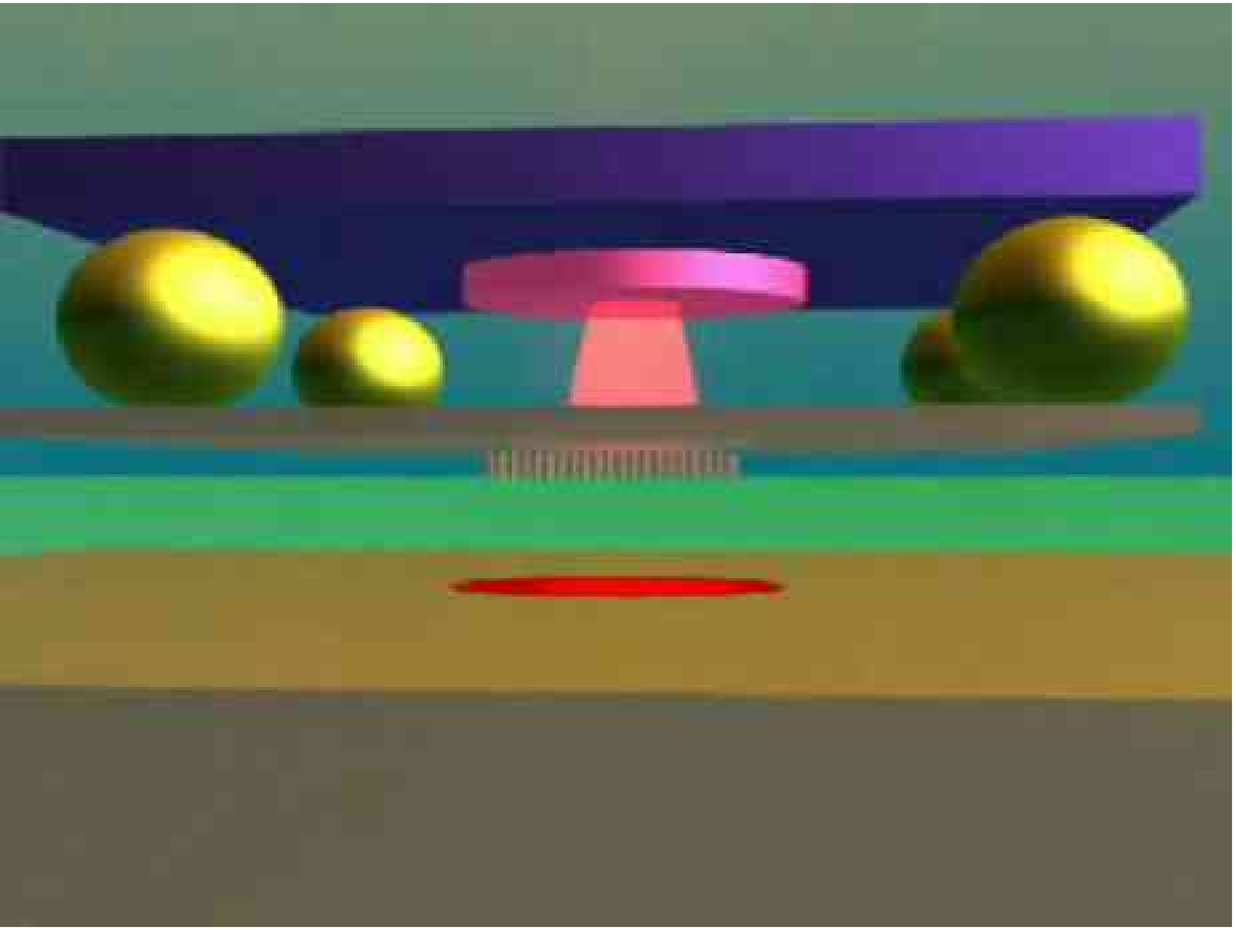


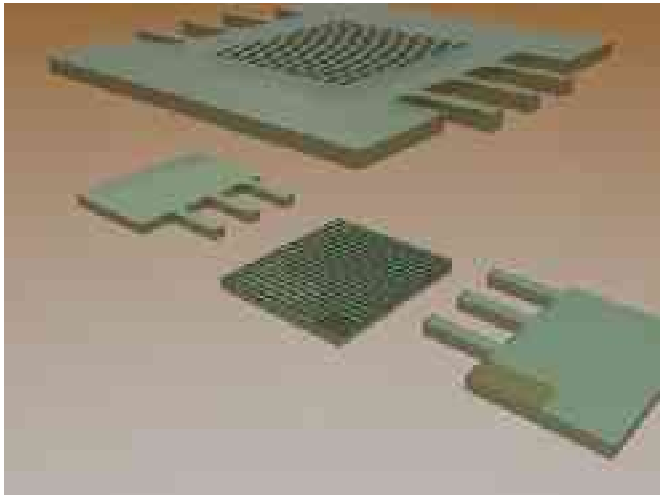
Noise floor approaches 10 fm/rt-Hz abve 100 Hz. Signal Peak at 1 Hz for a 50 pm amplitude of motion

Silicon Dual Grating Devices

- Having proven the ability to interact with light with laterally deformable gratings, we need:
  - More robust design.
  - Process that is easily integrated.
- By realizing such a lateral transducer, we can enable a new class of multi-axis accelerometer systems.
- We are not rewriting laws of optics or physics.
  - Merely demonstrating ability to use optical motion detection in a very compact system, with lateral motion detection.

2 Layer Grating





Near Field coupled grating structures in two layers.

Robust mechanical Design

Very flexible design parameters.

Extensible to multiple layers for active control of amplitude and phase across a broad band.

D. W. Carr, B. E. N. Keeler, G. R. Bogart, Hilton Head Sensors and Actuators Workshop, 2004.

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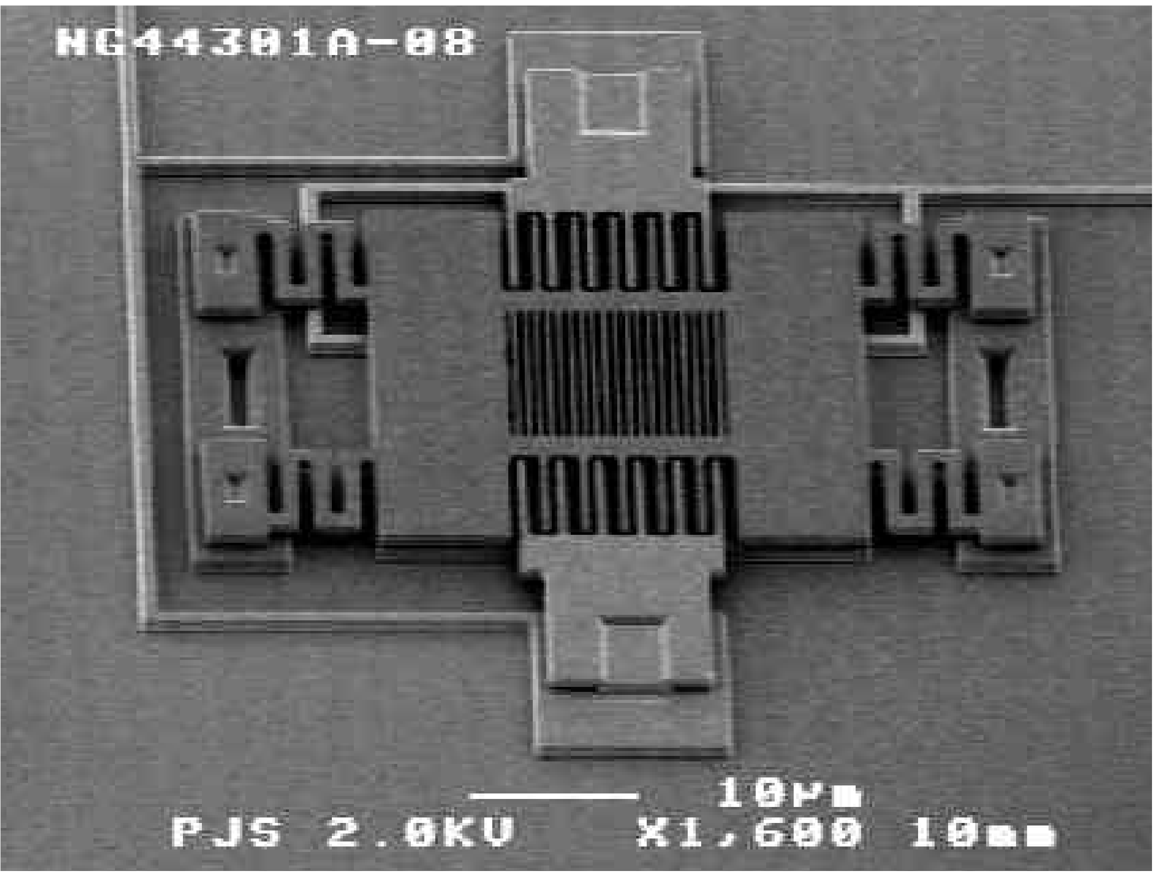
Dual Layer Grating Test Structure



- Test device used to verify the predicted optical properties of the grating.
- 0.865 micron silicon layers.
- Two identical grating levels.
- Minimum features of 150 nm.
- Both grating levels held at ground.
- Driving electrodes for two axis actuation.
- Grating area is 10 microns.
- Lateral Resonant Frequency is 3 MHz
- Q-Factor of 10^5 in Vacuum, 10^2 in air.

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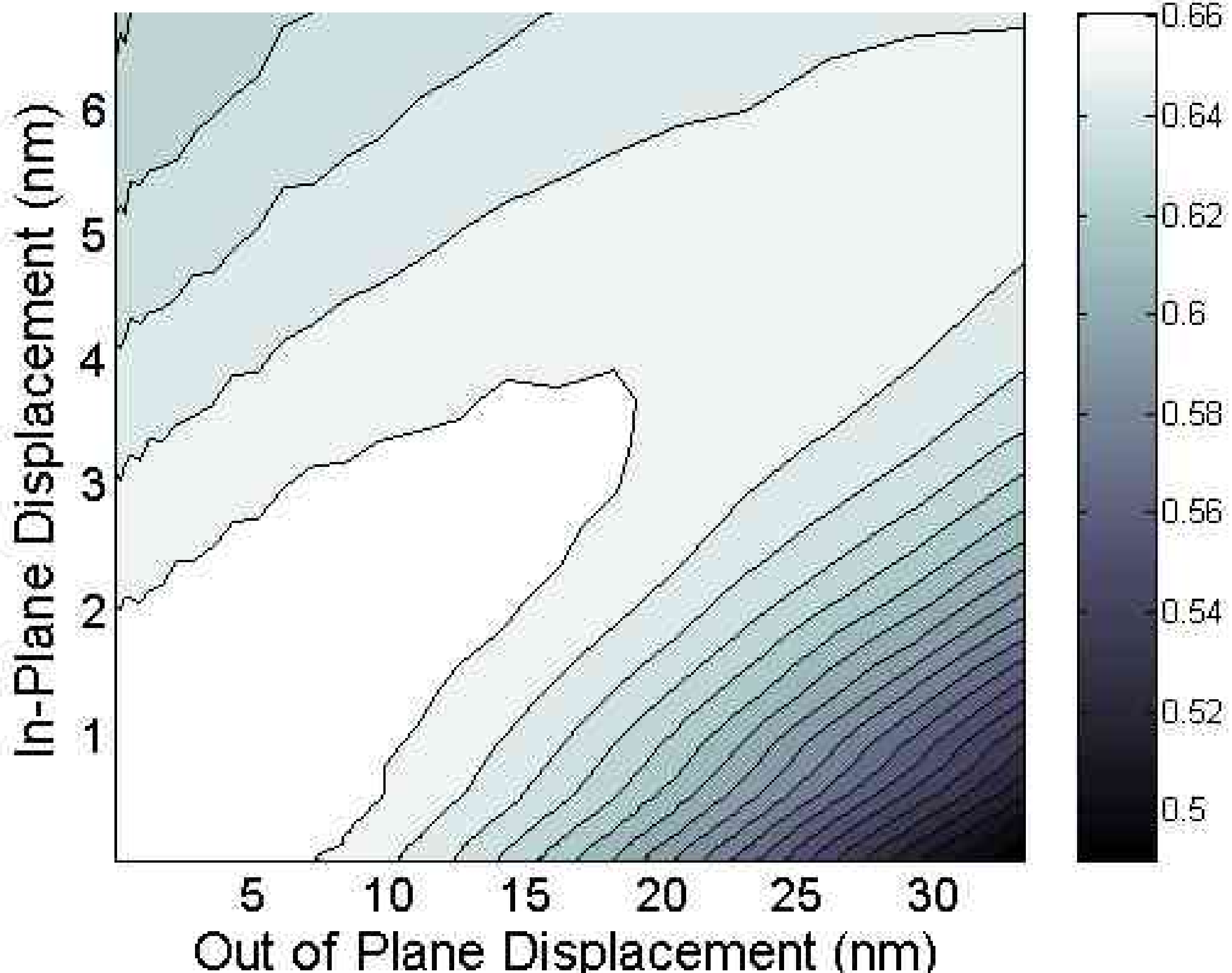
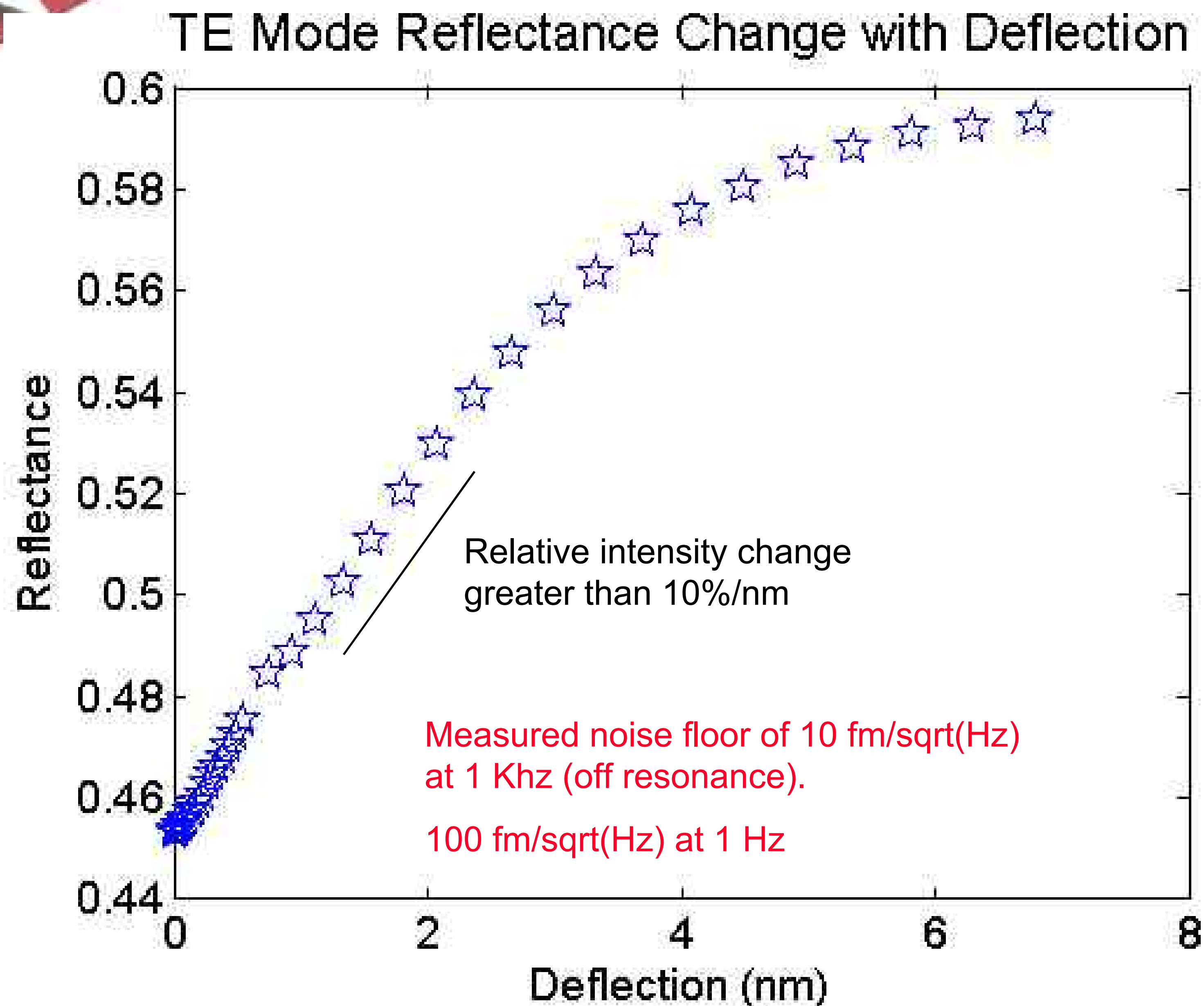
Observed TM Mode Reflectance with Displacement





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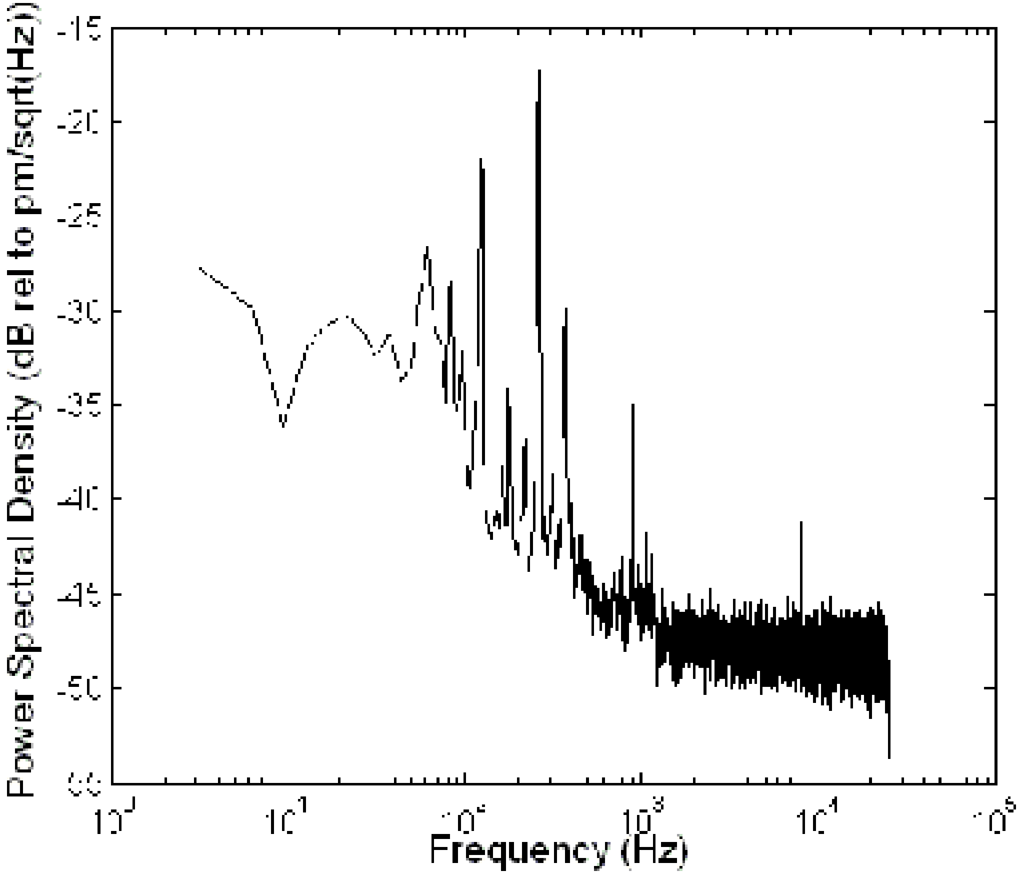
~10 fm Noise Floor
>120 DB Dynamic Signal Range (Open Loop)



FFT of data acquired at 50 KHz.

Drive signal applied to device at 8 KHz, corresponds to approximately 20 fm of motion.

Spurious noise peaks at lower frequencies can be further eliminated with improvements in the noise cancelling circuitry.

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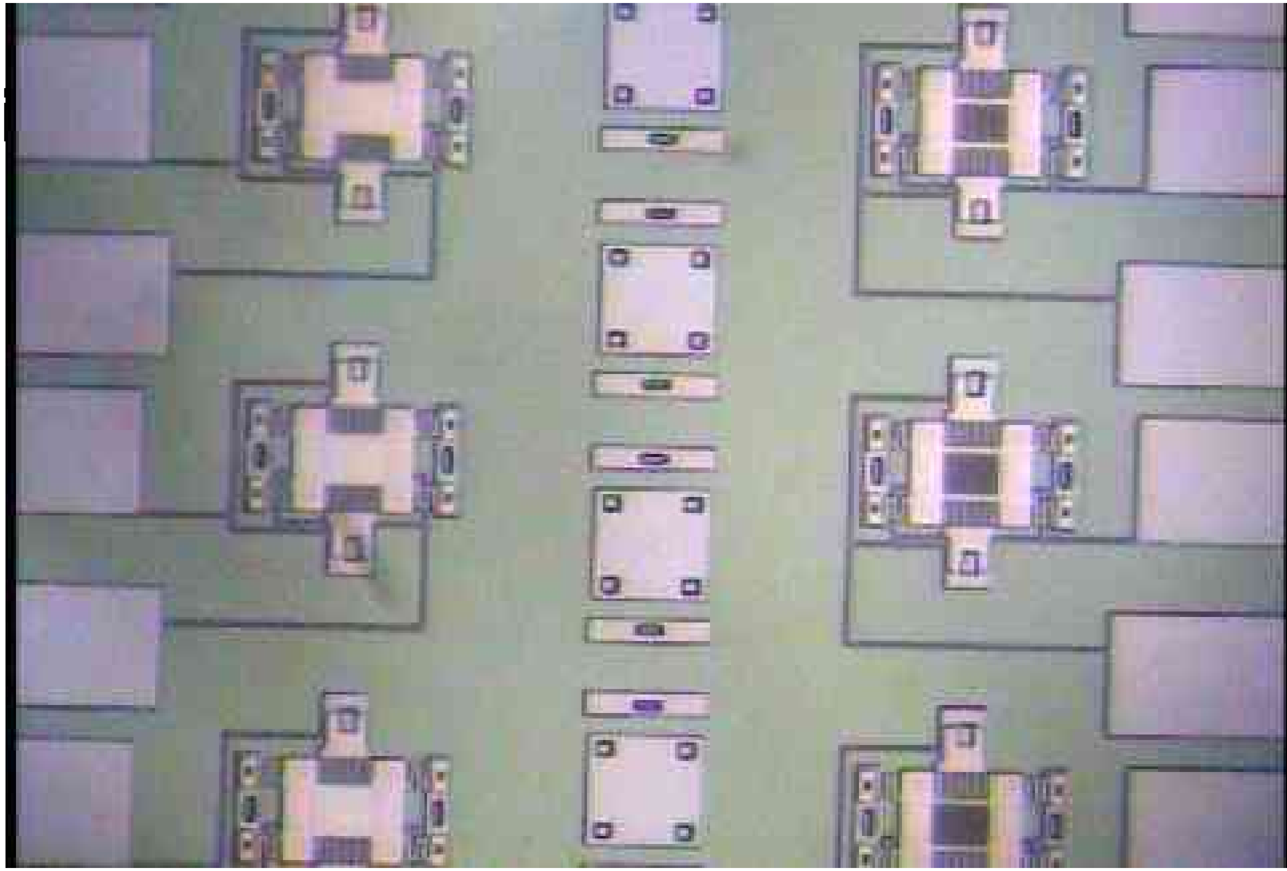
Devi

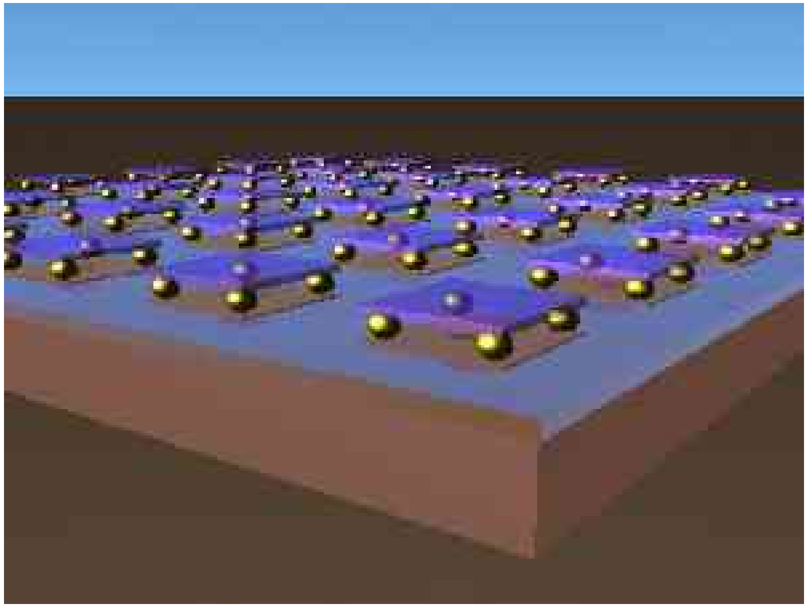


Device modulating at ~2 Hz, lateral displacement of 10 nm.

Sensor Arrays and Networks

Remotely powered, remotely sensed devices can be coupled together with coherent light sources to produce a robust sensor system that is immune electromagnetic interference.

Intelligent architectures enable remarkable noise reduction beyond a simple factor of $n^{1/2}$.



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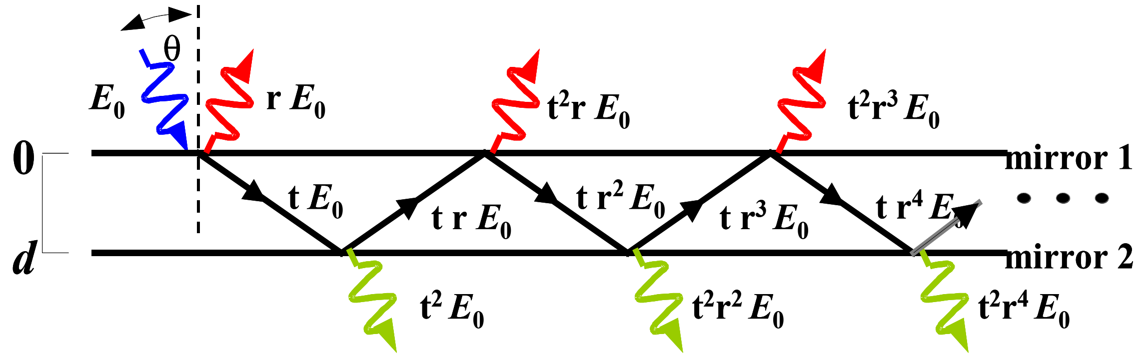
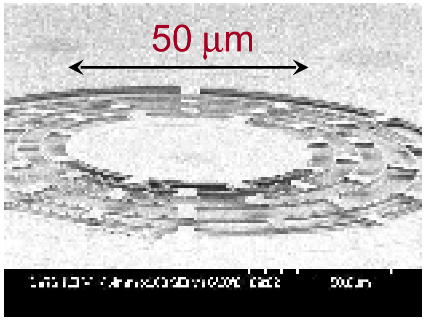
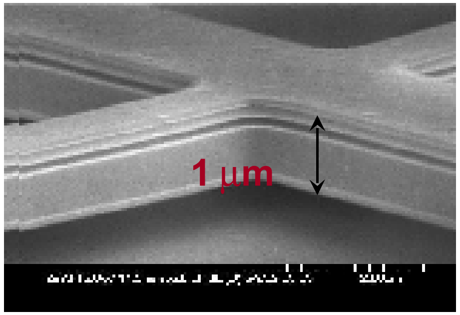
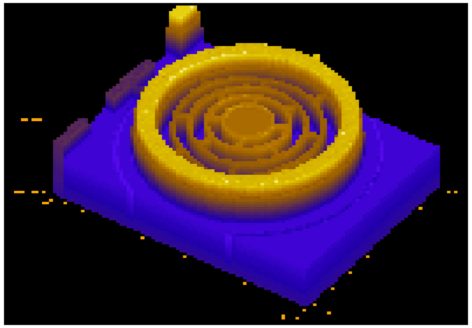
MEMS Ultra-Sensitive Accelerometer From SPAWAR Naval Research



Fabry-Perot Interferometer is comprised of two optically flat parallel mirrors where one of the two mirrors is allowed to move thereby adjusting the spacing between the mirrors. If the spacing is a integral multiple of half wavelengths, a resonance occurs with a corresponding peak in transmission.(Courtesy of Richard Waters, SPAWAR)





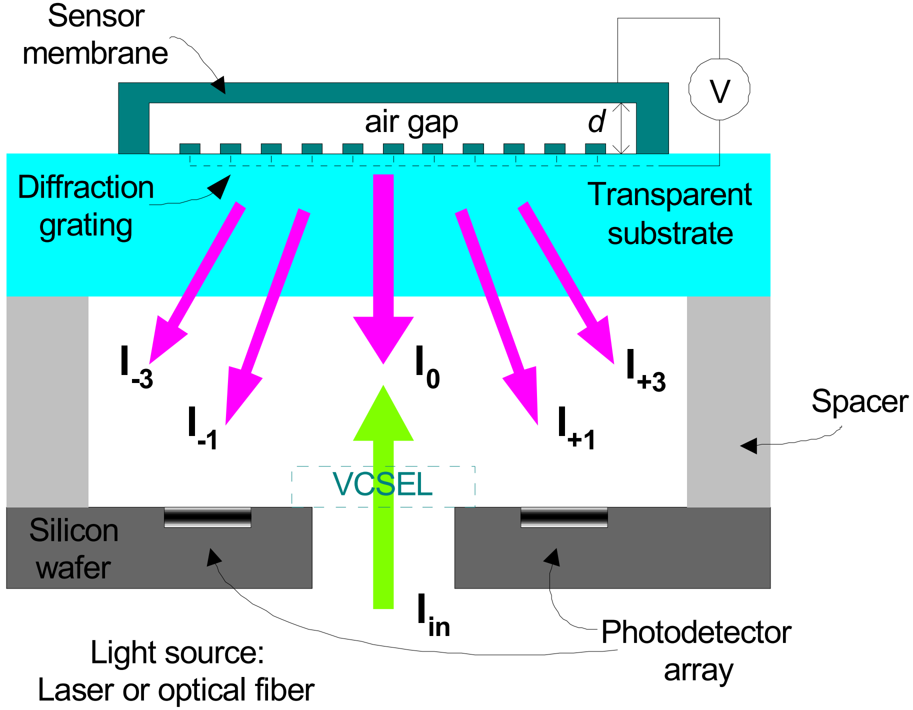


World record transduction > 75 mA/μm *

MEMS USA Results to Date

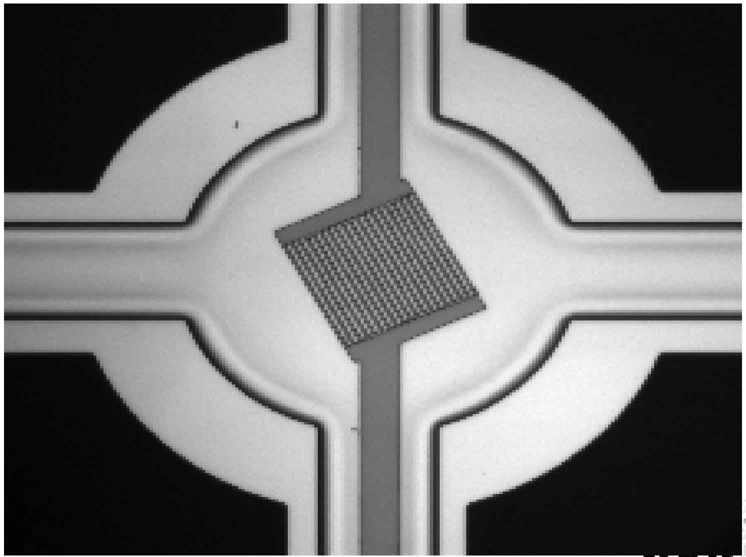
- Novel MEMS USA Approach utilizes wavelength of light to detect minute perturbations of a proof mass attached to a spring.
- Transduction Approach can be applied to gyroscopes / other MEMS sensors.
- MEMS USA has “Transistor” Action
  - PWM Laser to avoid 1/f Noise
  - Fabry-Perot Cavity has Inherent Averaging
  - Zero Cross-axis Sensitivity
  - Small Size allows Arrays of Sensors
- Laser Power is “BIG Knob” for Increasing Sensitivity
  - Have all the other “Knobs” as well: Size (Mass), Spring Constant, ...
- Measurements to Date:
  - Transduction: 75 mA / μm
  - SNR: 600,000:1 (19 bit accuracy with no Temperature Control)
  - Modulation: 55%
  - Minimum Detectable Displacement: 4 fm/rHz

Optical Transducers for Acoustic Sensors at Georgia Tech



Courtesy of Neal Hall and Levent Degertekin.

They have demonstrated outstanding performance of a compact acoustic sensor array.



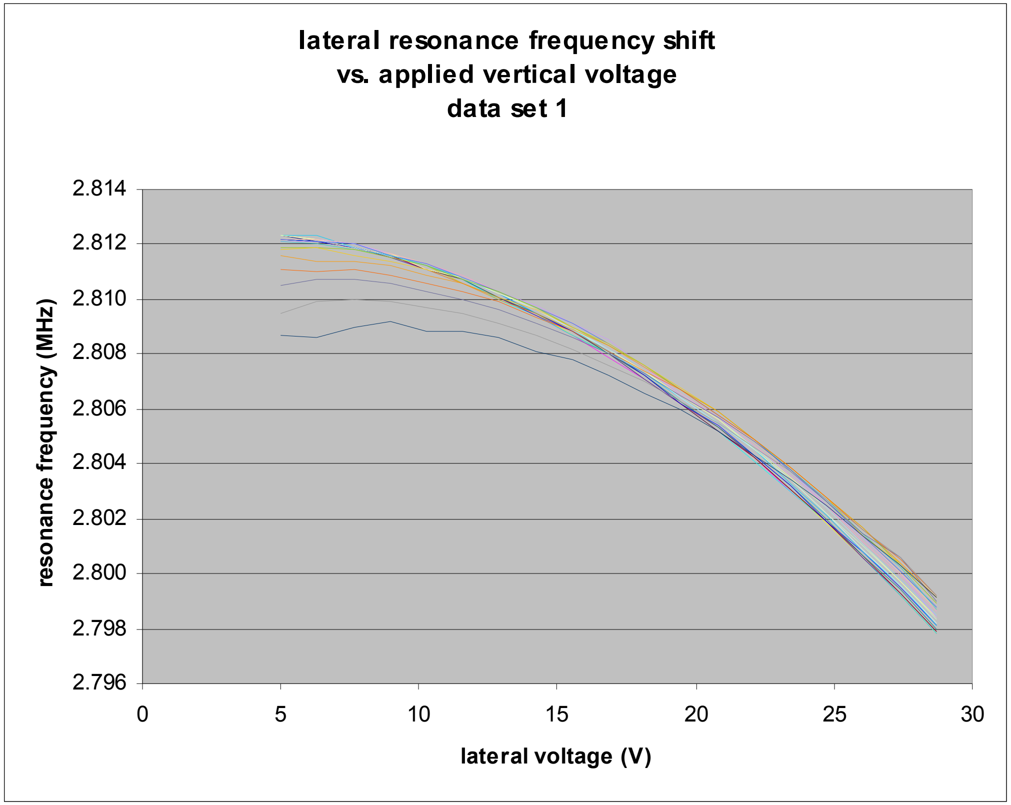
Ongoing Work

- Integrating transducer with proof mass for force measurements.
- Optical sub-assembly integration.
- Studying new materials to enable flexible polymeric sensor components.

Conclusions

- **Optical transducer technology is the most logical choice for intelligent sensor systems.**
  - Low cost
  - Compact
  - High signal (current/nm), simpler electronics.
- **We have designed and tested a new class of optical NEMS devices utilizing laterally deformable gratings.**
- **We are in the process of incorporating this and related technologies into inertial and acoustic sensor systems with a broad range of applications.**

Experimental results - frequency shift



Resonance frequency shift:

$$f_r = \sqrt{f_0^2 - \frac{\varepsilon}{4\pi} \quad \alpha \quad \frac{}{d_0^3} V_{dc}^2}$$

Using simple electrostatic model

A = overlap area

m_{eff} = effective modal mass

d_0 = initial beam separation

V_{dc} = applied dc voltage

α = fitting parameter, proportional to capacitance

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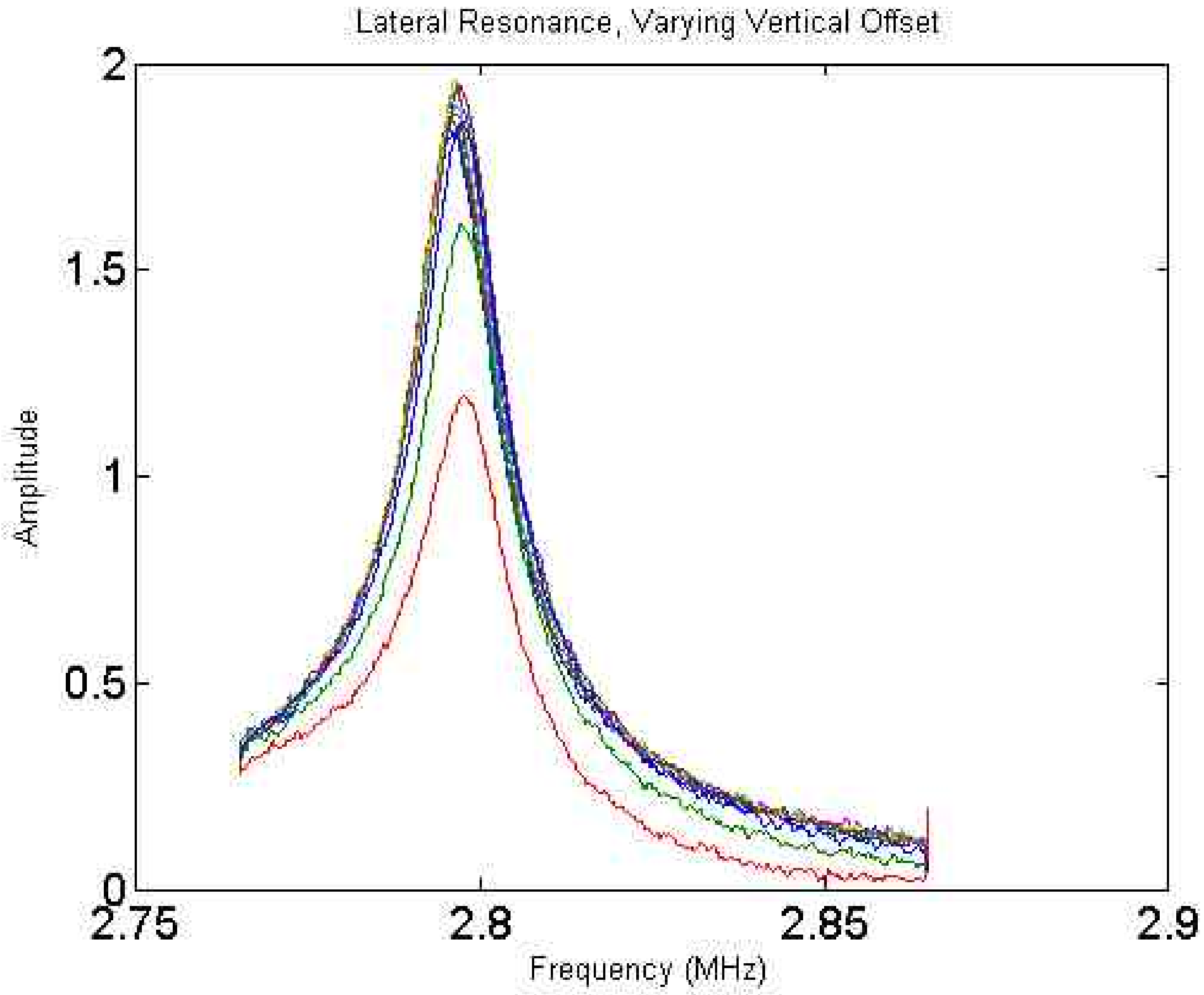

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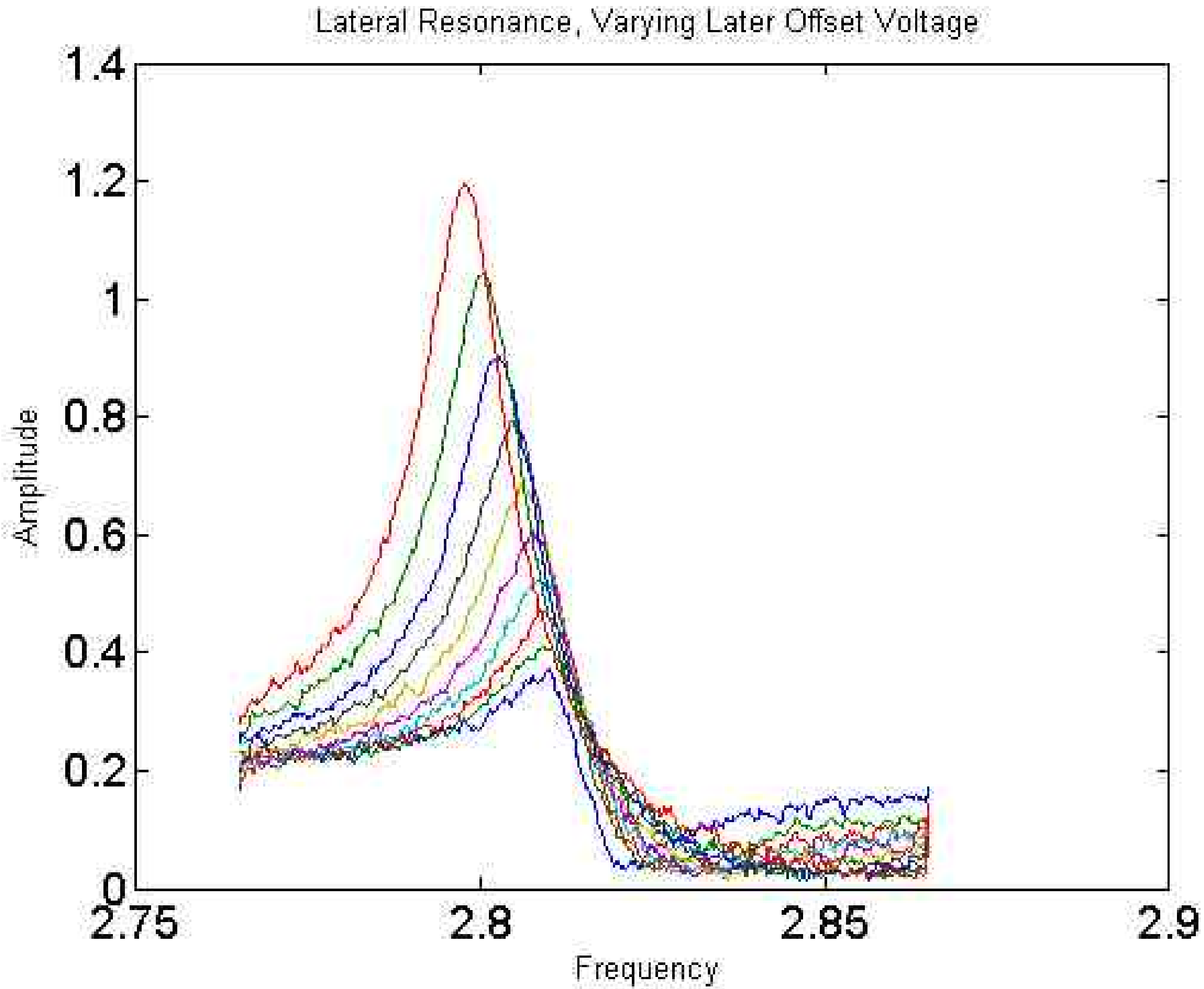
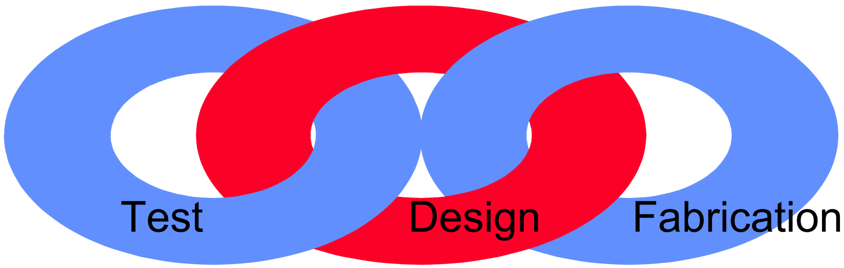

Lateral Resonance, Varying Later Offset Voltage
Amplitude
Frequency
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2.75
2.8
2.85
2.9

Test-Design-Fabricate Interlinking



Overlap of all three activities is vital for success.

Designers must intimately know device specs as well as the fabrication process. Fabrication process leaders need some understanding of device specs, and a fundamental Understanding of the design and how it impacts the process.

To move towards a manufacturable process, care must be taken at each and every step to understand all process issues, feeding these back into the design.

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