Characterising MEMS: A comparison of the techniques available

Jim Burdess, Alun Harris, John Hedley, Barry Gallacher

Presentation overview

- Introduction – why characterise?
- Basic equipment
  - Mounting and actuation
  - Vibrometer, profiler, Nd:YAG laser
- Examples
  - Development of 3 axis gyroscope
  - Edinburgh University, NPL
- Further developments – Raman spectroscopy
- Summary

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Introduction

- Why characterise?
- Are they functional?
  - Yes – do they operate as expected (e.g. frequency)?
  - No – why not?

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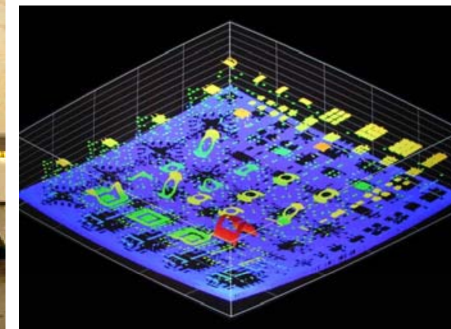
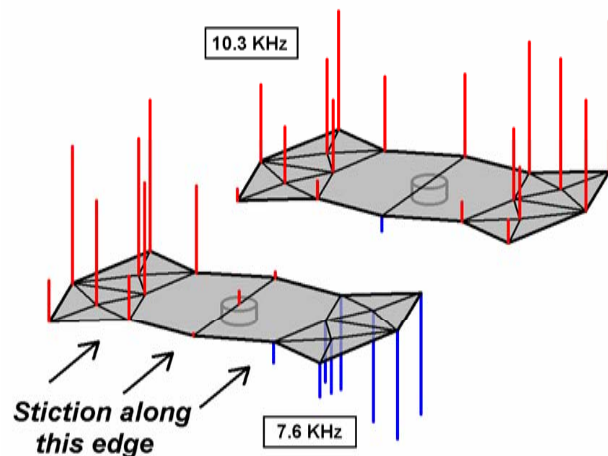
Why optically characterise?

- Independent method of testing to localise fault – i.e. mechanical, electrical, etc.
- Non-contact





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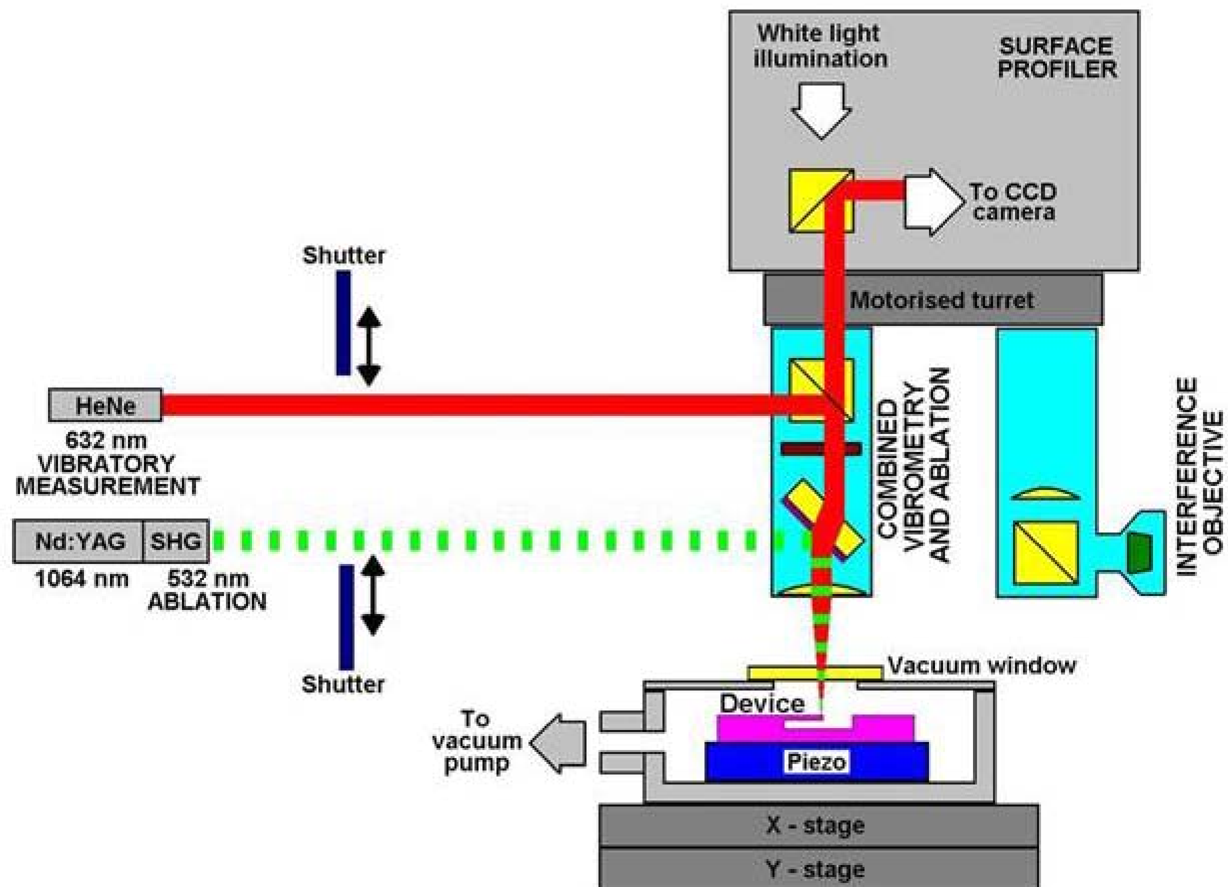
The lab

Equipment schematic



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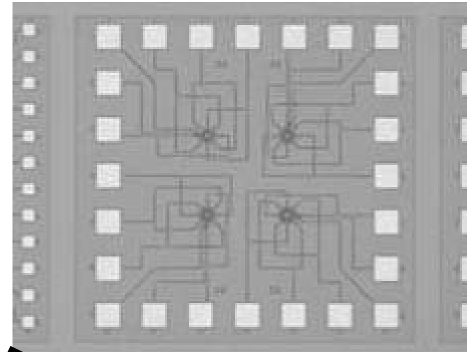
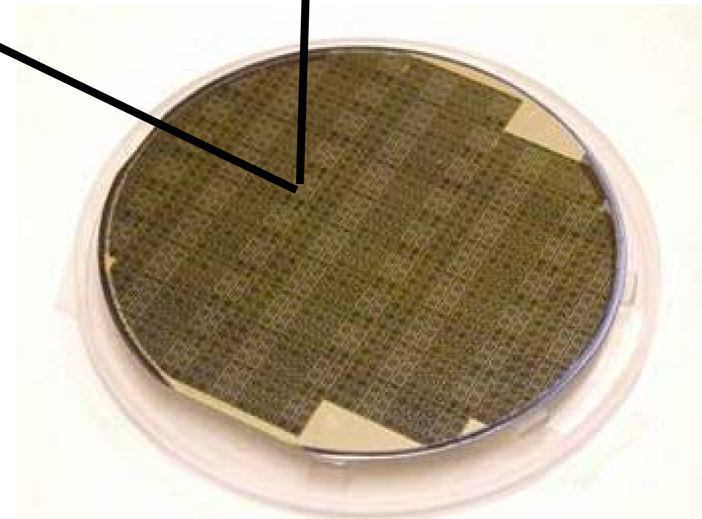
Mounting and actuation

- Mounting requirements
  - Rigid fixing
  - Easily attached / removed
  - Operational in a vacuum
- Actuation requirements
  - Drive device without connections to wired electrodes
  - Tested under vacuum





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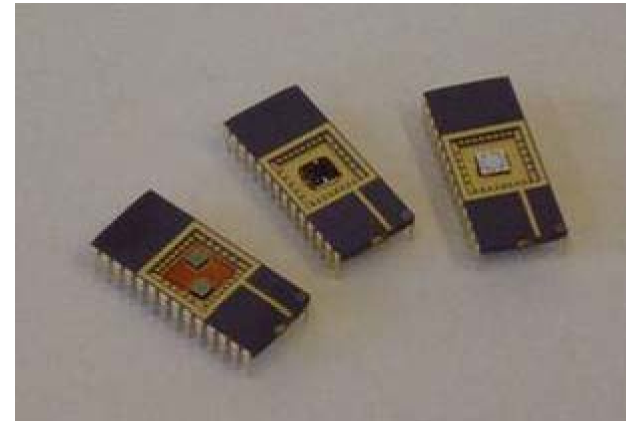
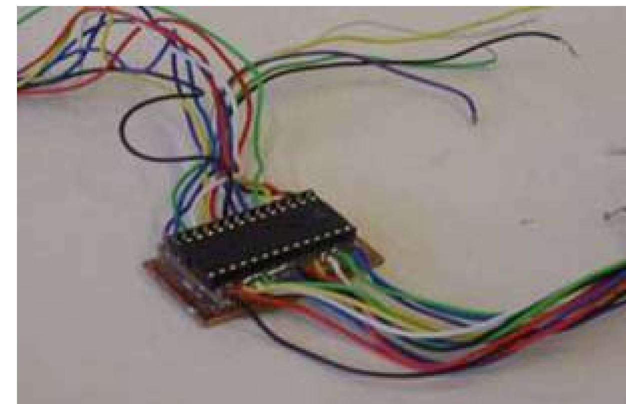
Chip mounted

- Preprocessing
  - Photoresist as glue?
- Simple plug in
  - Less chance of device damage
- Ready for wire bonding
- Size limited! ($1cm^2$)





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Wax mounted

- Effective
- Quick
- Messy
- End of processing
- Copper disks

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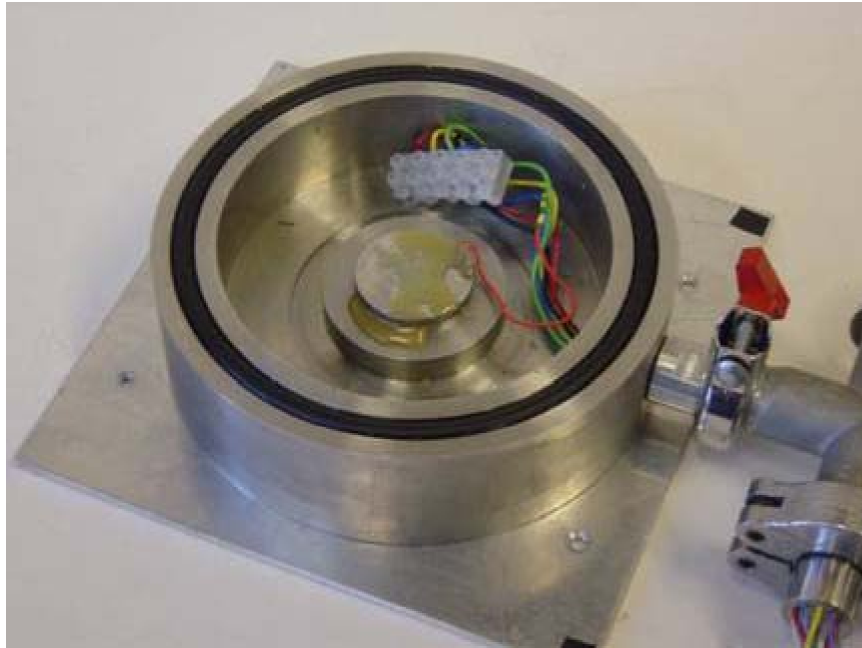
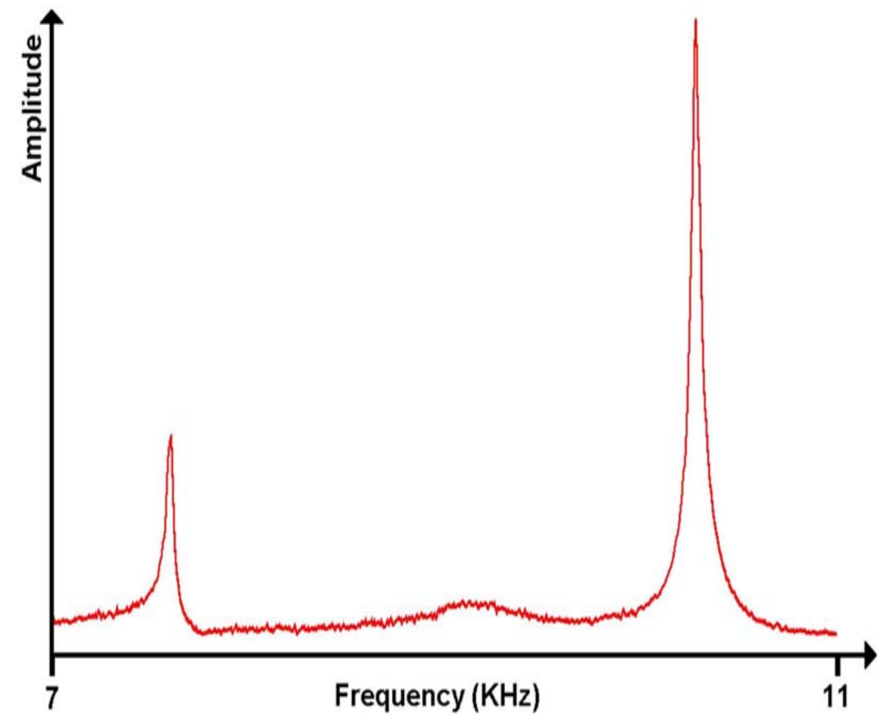
Mechanical actuation *(piezo disk)*





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Mounting: Pressure plate

- Larger samples (wafer)
- Spacer required
- Stresses?
- Continued processing

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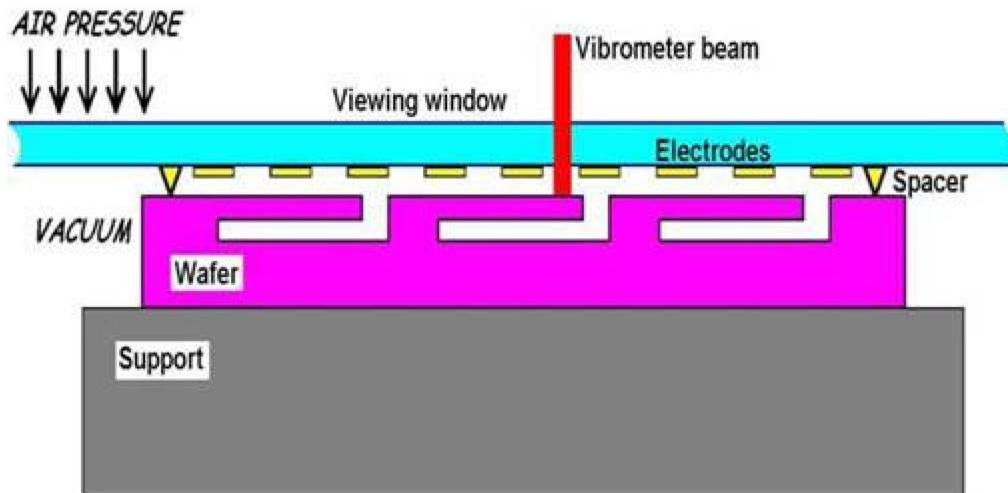
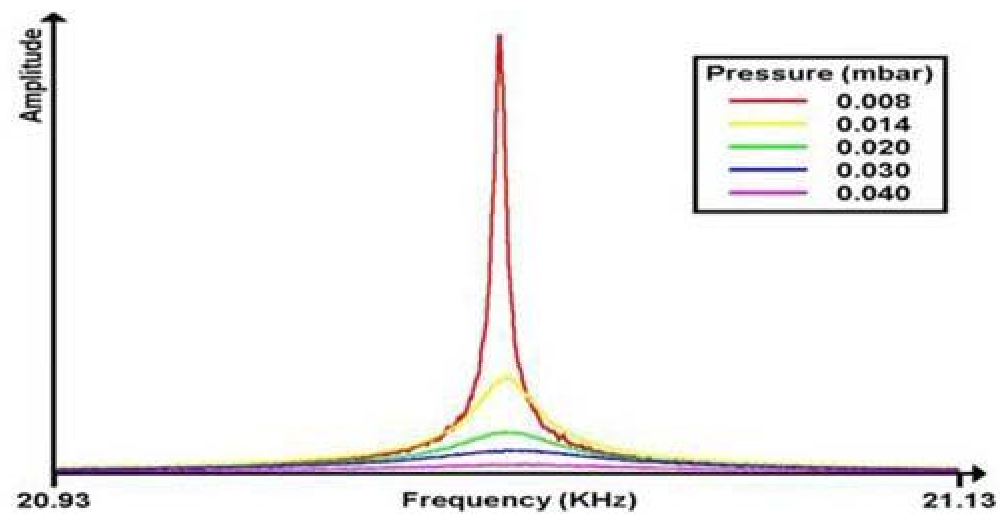
Electrostatic activation





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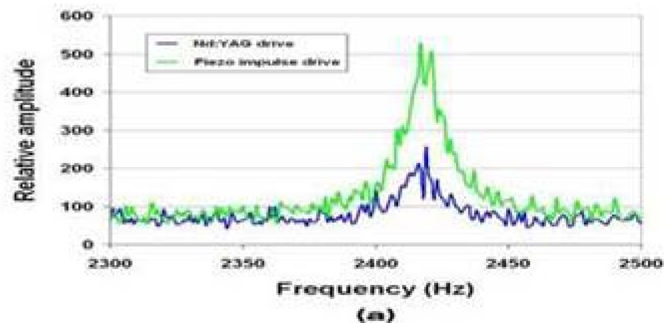
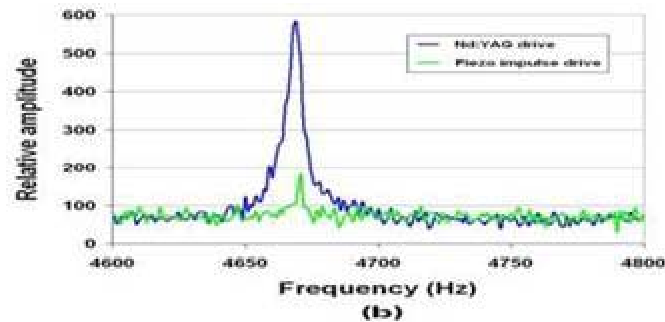
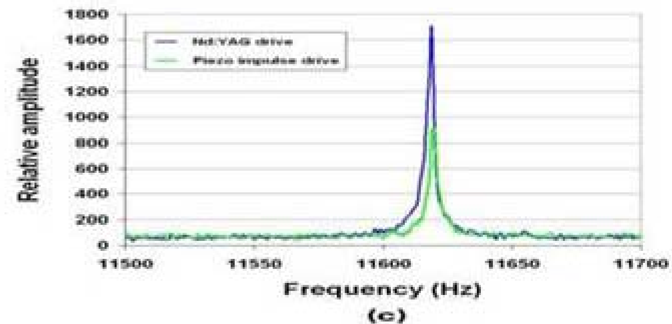
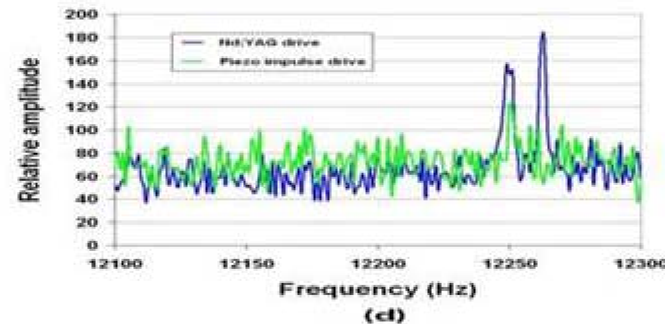
Optical actuation

- 20 Hz Nd:YAG laser
  - Focusing causes ablation
  - Collimated beam
  - Impulse response









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Thermal expansion ?

- Energy absorbed: $$E_{abs}(z,\delta z) = \left(E_{incident} \times \frac{l^2}{\pi r^2} \times (1-R)\right) e^{\frac{-4\pi\kappa z}{\lambda}} \left(1 - e^{\frac{-4\pi\kappa\delta z}{\lambda}}\right)$$
- Temperature increase: $$\Delta T(z,\delta z) = \frac{E_{abs}(z,\delta z)}{l^2 \delta z \rho c}$$
- Expansion: $$\Delta l(z,\delta z) = l\alpha\Delta T(z,\delta z)$$

$$E_{incident} \approx 1mJ$$
$$R = 37\%$$
$$r = 3mm$$
$$\alpha = 2.6\times10^{-6}K^{-1}$$

Depth δz (μm)	Temperature increase (K)	Expansion (nm)
0→1.5	6.1	4.8
1.5→3	2.1	1.7

- To relieve stress, accelerometer must flex – vertical displacement ~80nm.

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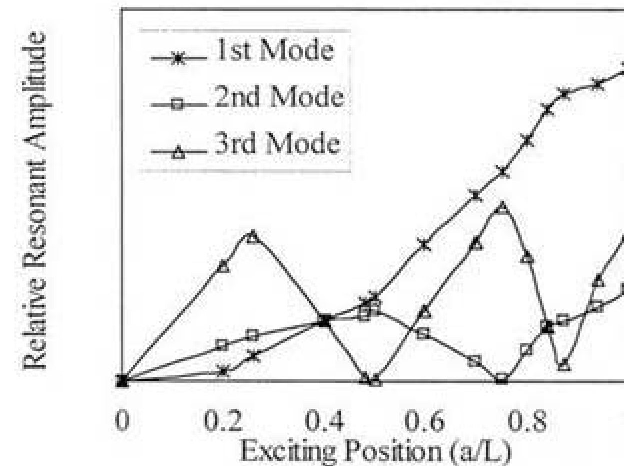
Which mechanism ?

- Measurements comparable with piezo displacement of ~100nm.
- ➔ thermal mechanism
- ***However,*** Yu et al tried point heat excitation
- ➔ photon momentum



The resonant amplitude as a function of the exciting position. In the figure, the exciting position a represents the distance from the hinge.

Sensors and Actuators, 77, 187-190, (1999)

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Polytec laser vibrometer

- Specifications:
  - wavelength 632 nm
  - frequency range:
    - 1.5 MHz (velocity)
    - 20 MHz (displacement)
  - picometer resolution
  - 20 mm working distance
- ➢ Rapid determination of natural frequency and damping
- ➢ Determination of modeshape (time consuming)

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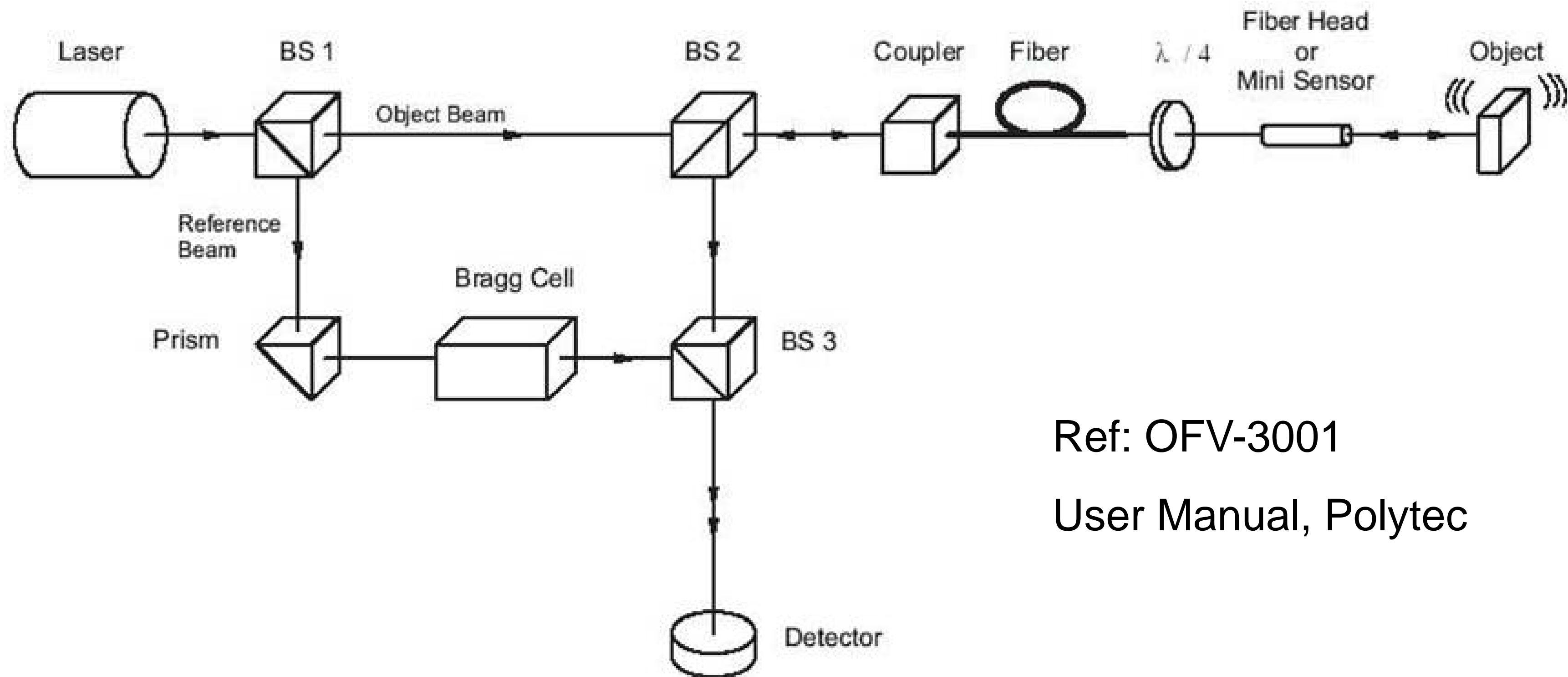
Schematic of operation



Ref: OFV-3001

User Manual, Polytec

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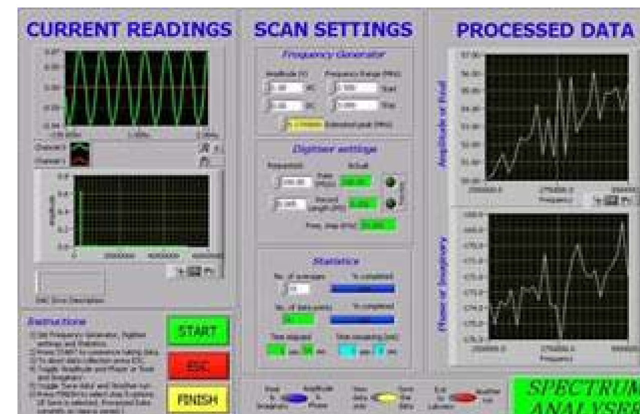
Analysis

- 100 KHz analyser
  - 2 channel 21 bit
- 100 MHz (2.5 GHz)
  - 2 channel 8 bit

- Random noise
- Swept sine
- Impulse



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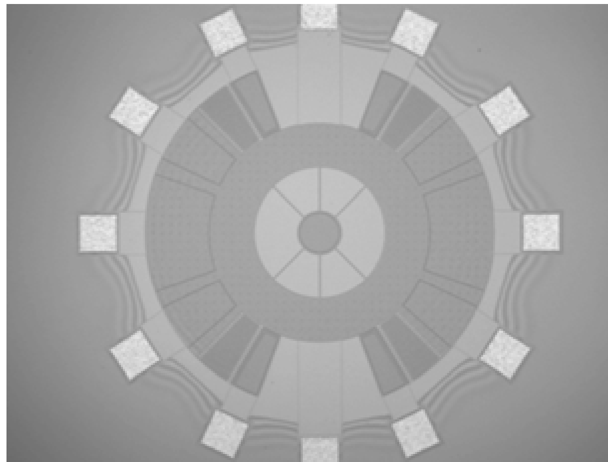
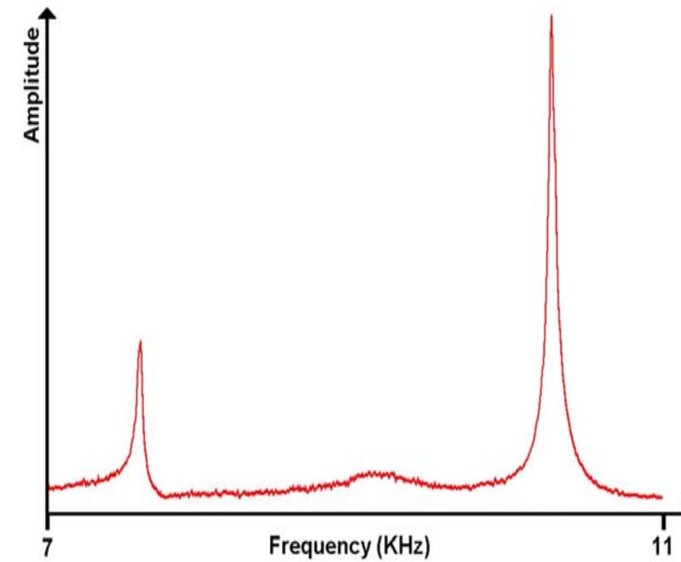
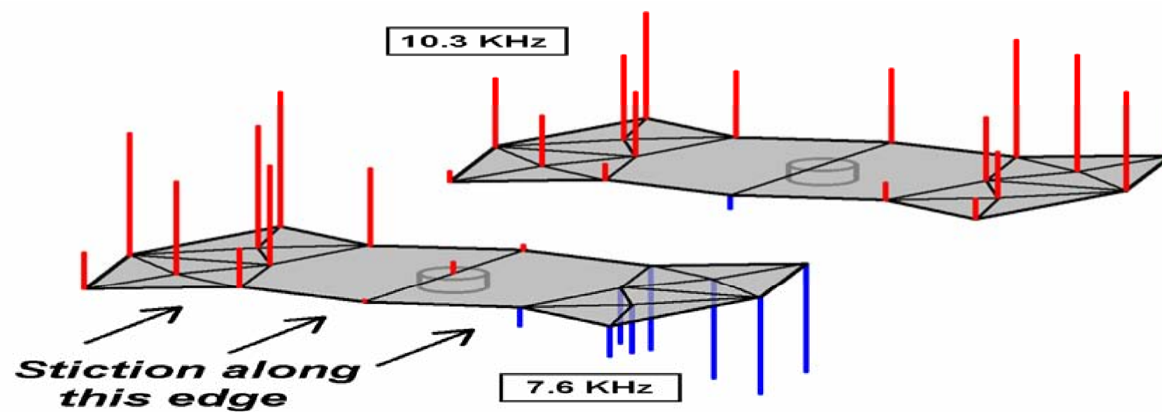
Typical measurement







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Zygo NewView surface profiler

- Specifications:
  - 2.5X Michelson to 50X Mirau objectives
  - 20X adapted Linnik objective
  - 5.6 x 4.2 mm field of view (larger areas by stitching)
  - 640 x 480 data points
  - 0.1 nm resolution (over 5 mm)
  - 2.4 um/s scan speed
  - 10 mm working distance

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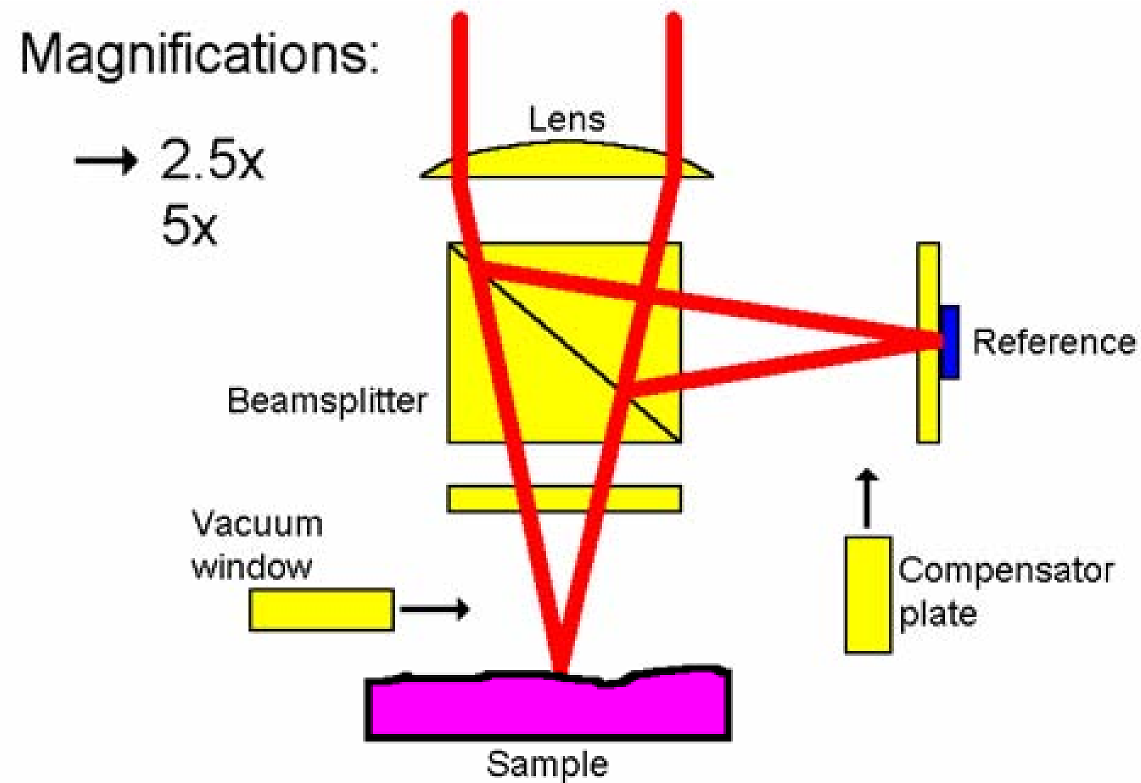
Schematic of operation



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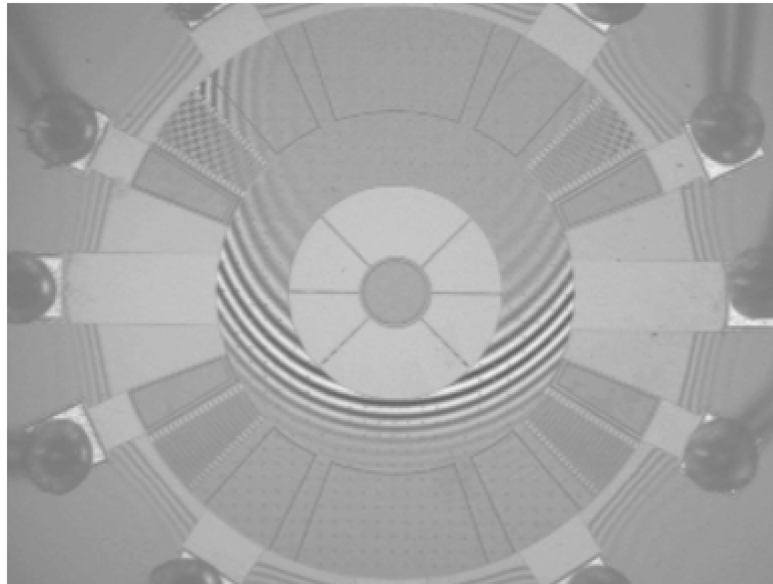
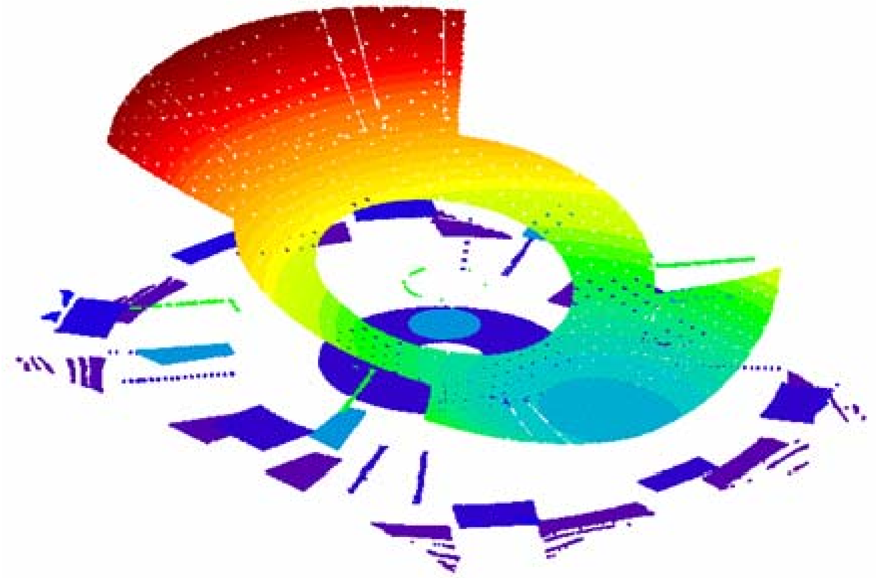
Typical static measurement

QinetiQ bowtie gyroscope.





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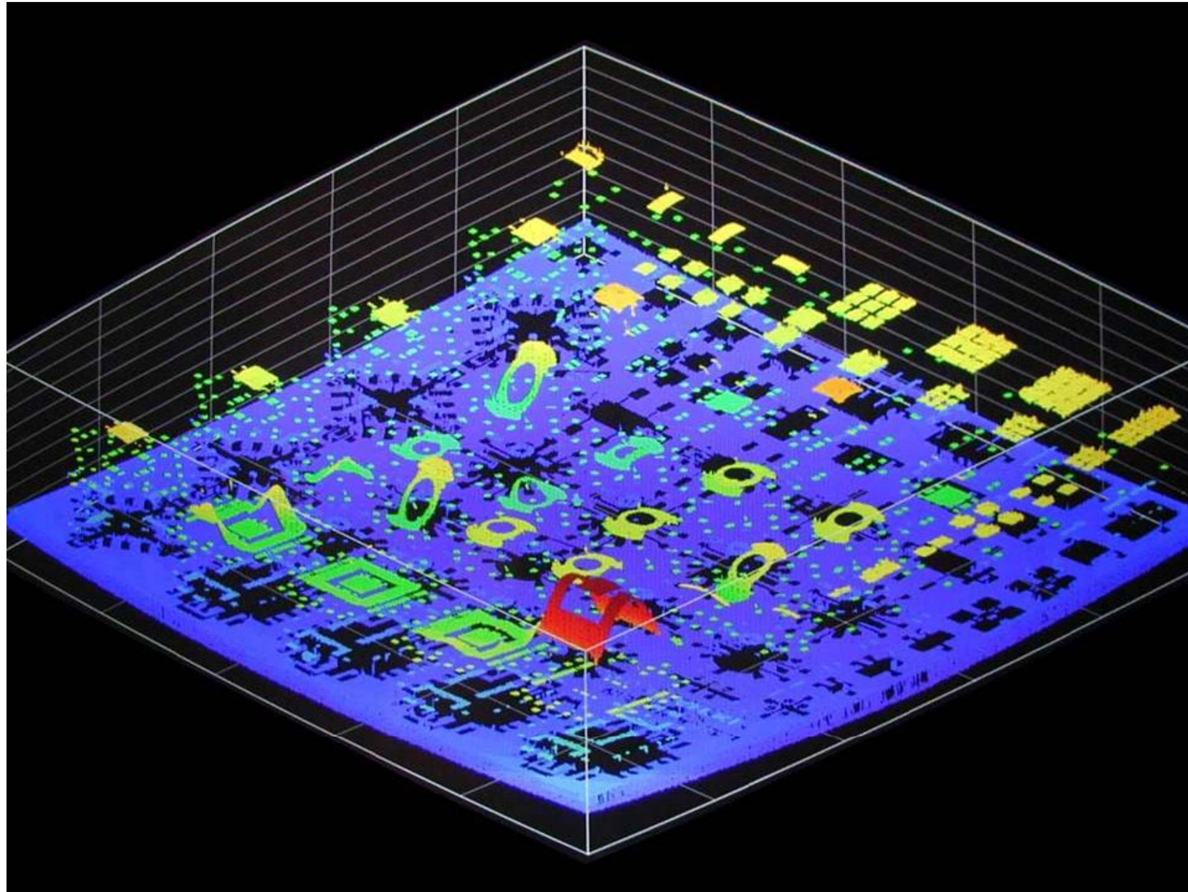
Typical static measurement



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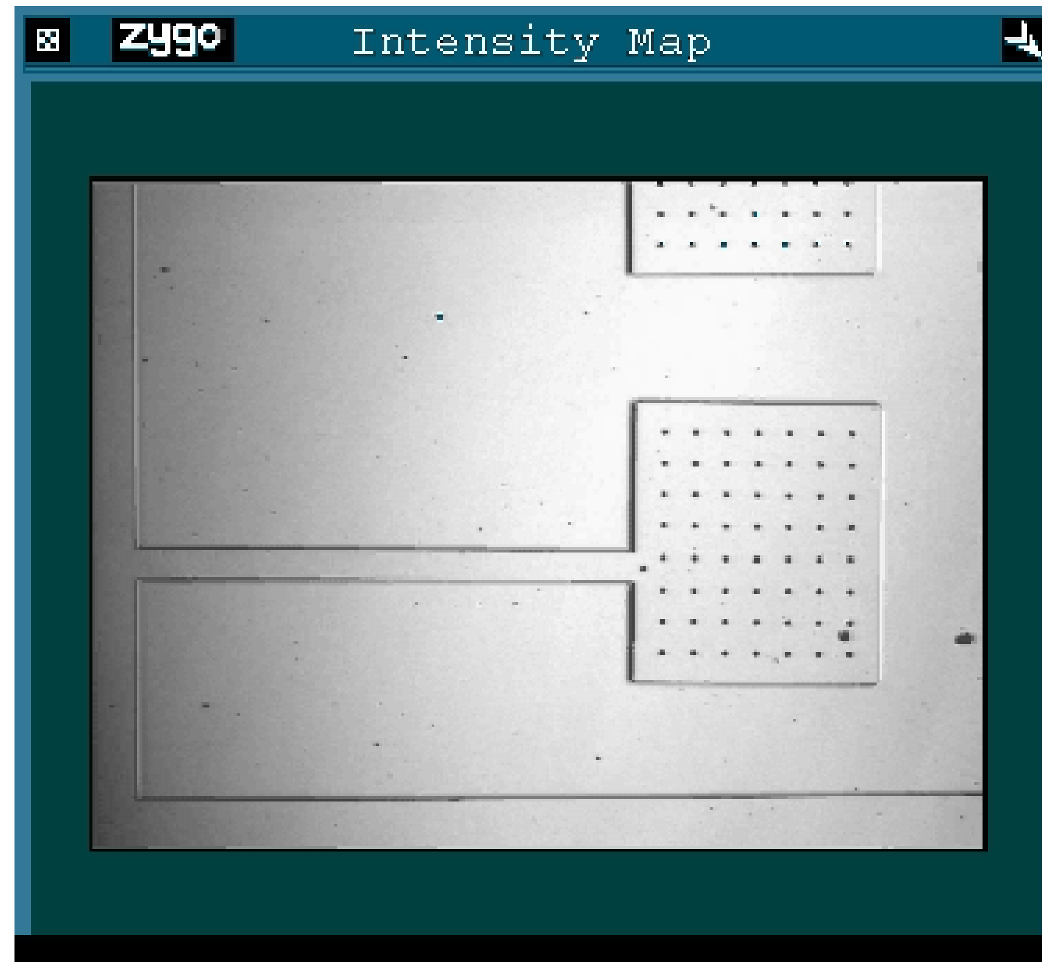
Typical dynamic measurement



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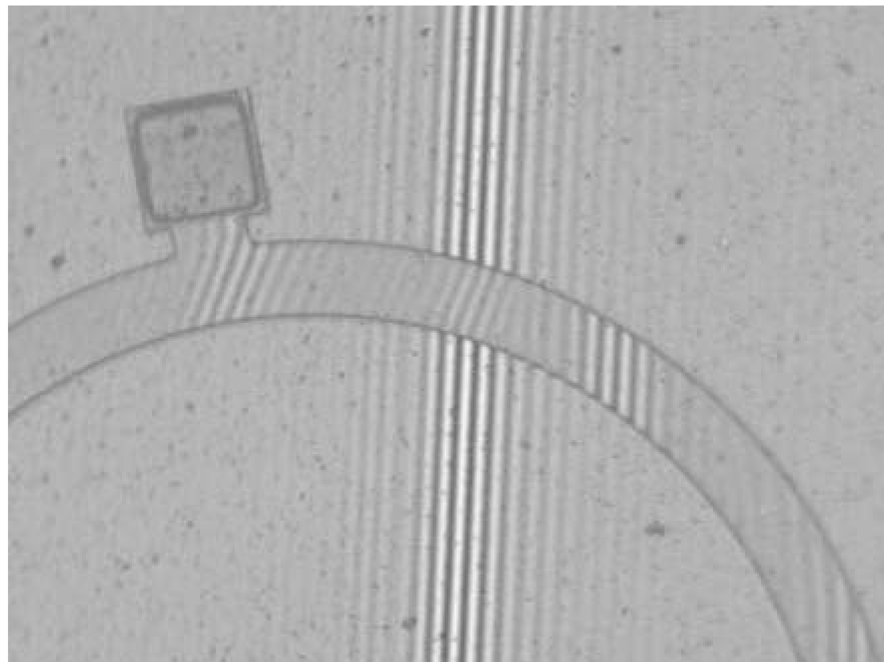
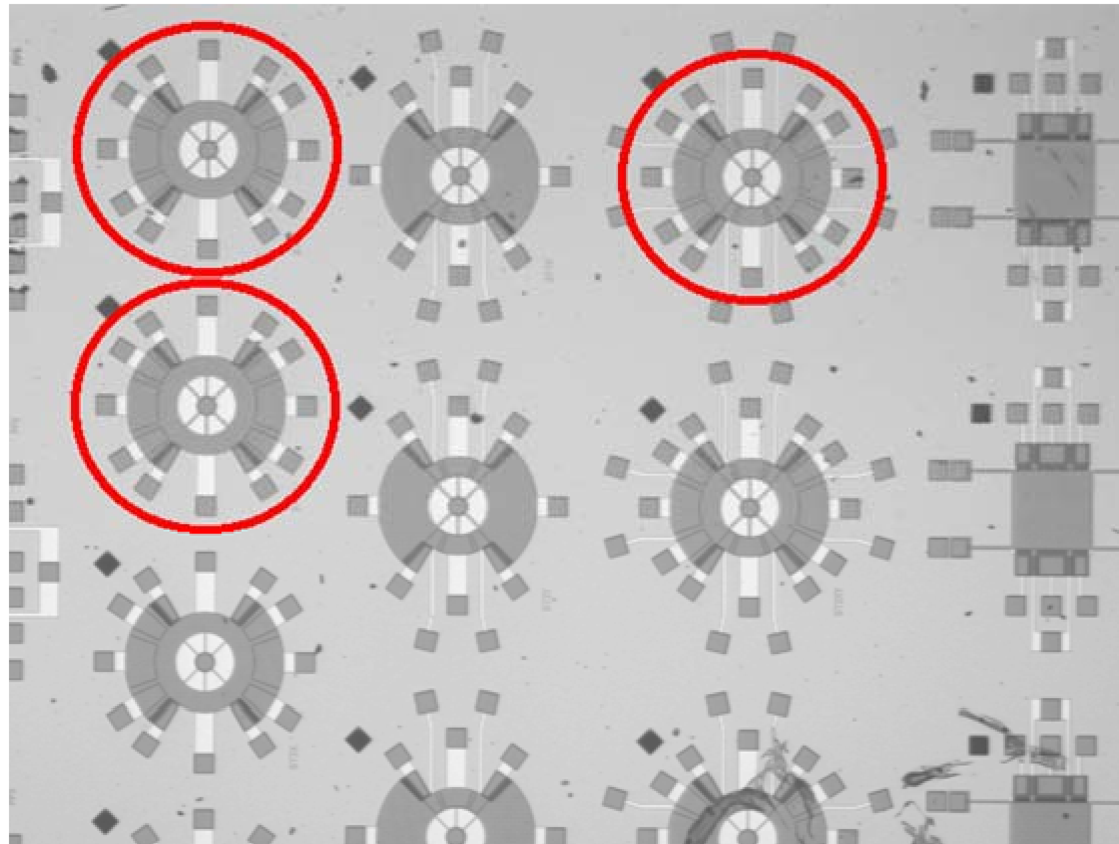
Problems

- Transparent layers
  - Appears as holes rather than hills
  - Multiple fringe sets



Alternative dynamic measurement



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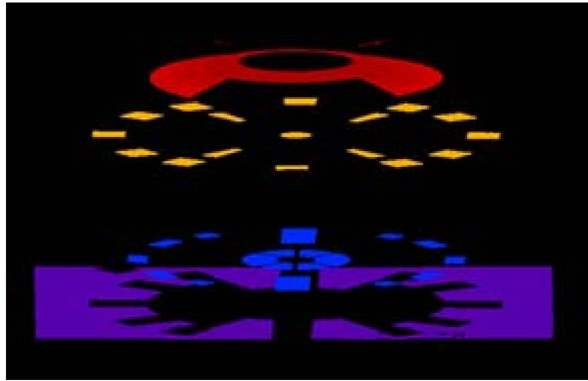
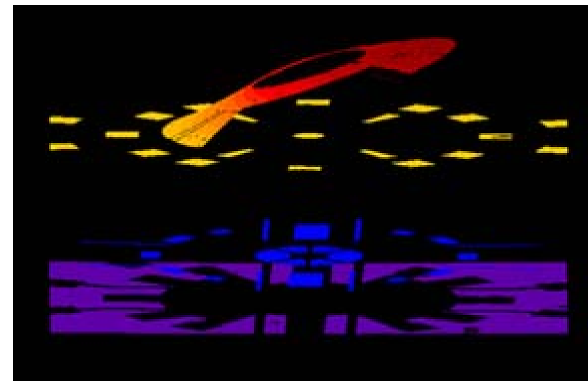
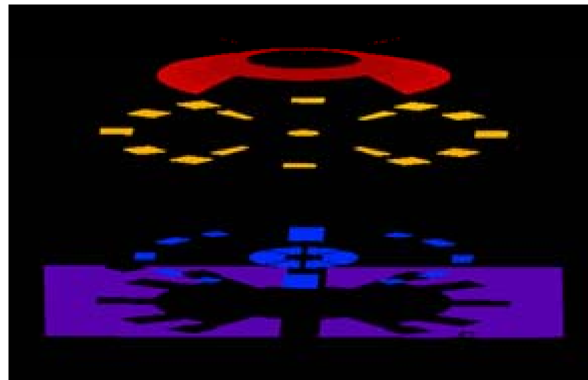
Step 1: Profile







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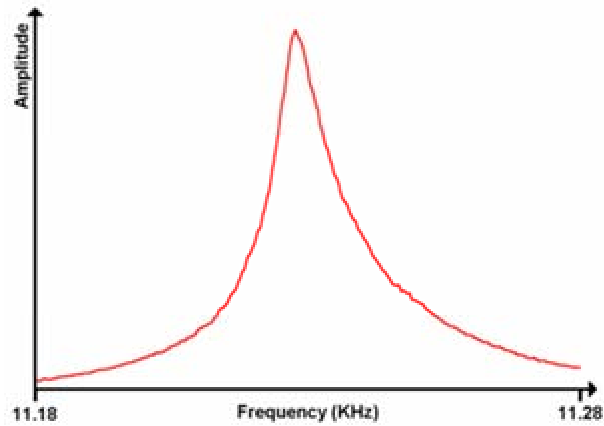
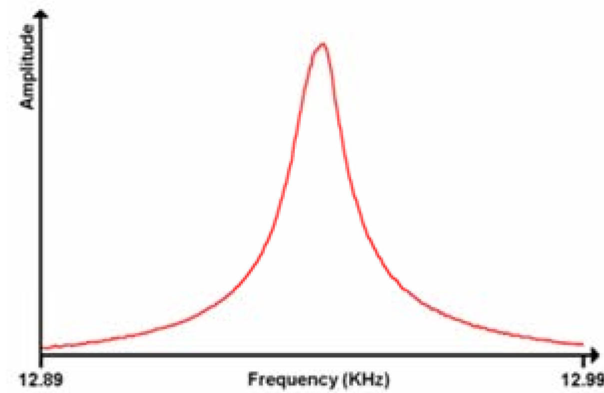
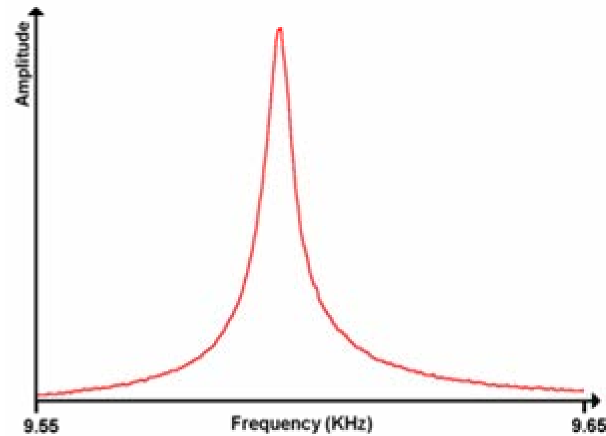
Vibrometer measurement







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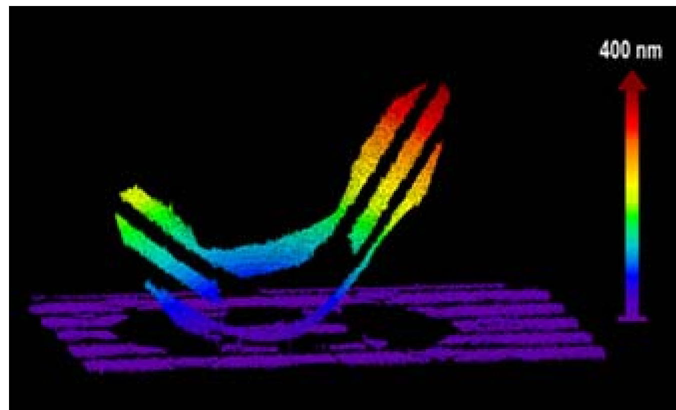
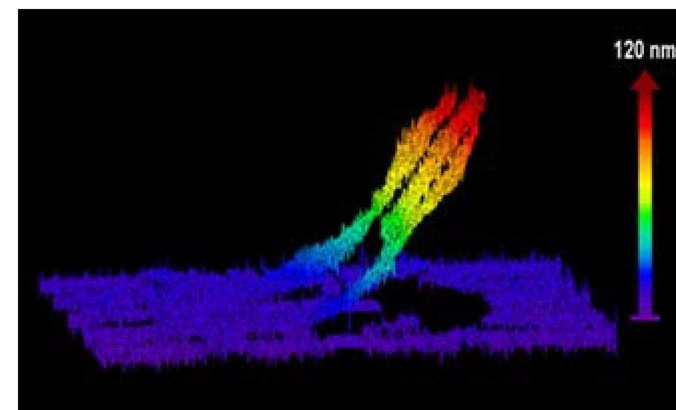
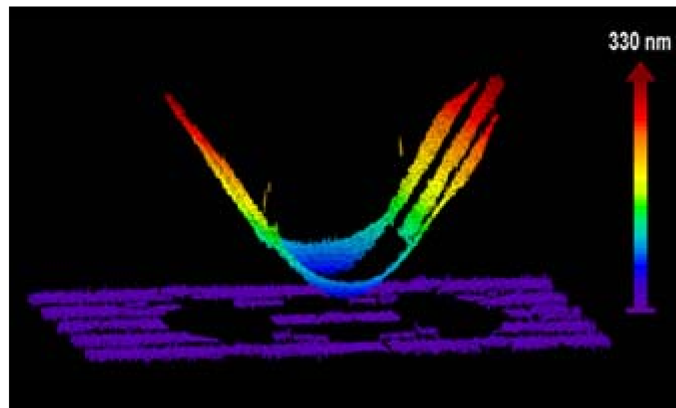
Step 2: Apply V and find difference







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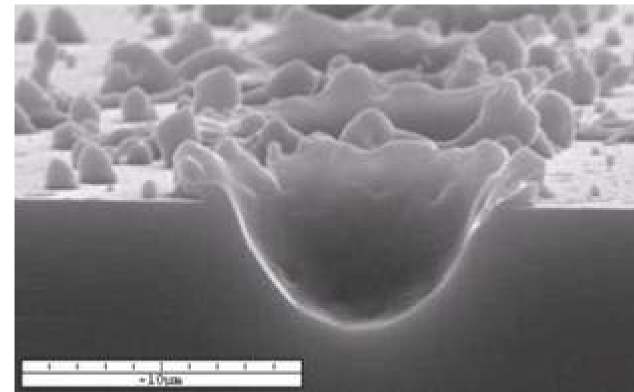
MEMS modification

- Characteristics:
  - Wavelength 532 nm
  - Energy <160 mJ
  - Pulse width 4 ns (20 Hz)

- Debris is problematic



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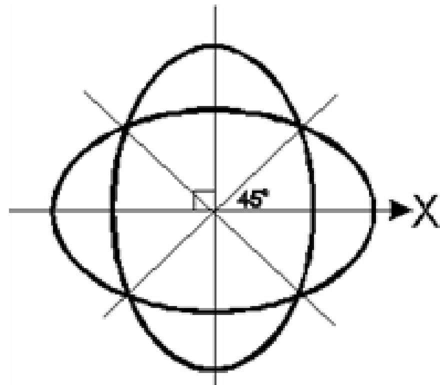
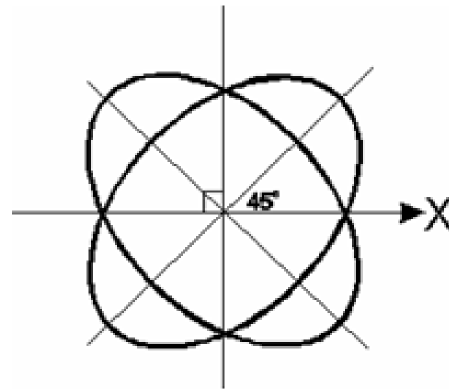
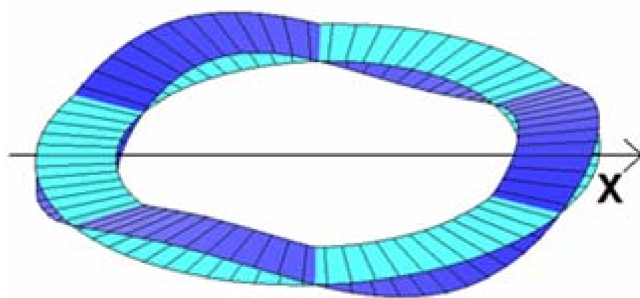
Ex. 1: 3-axis gyroscope (B. Gallacher)



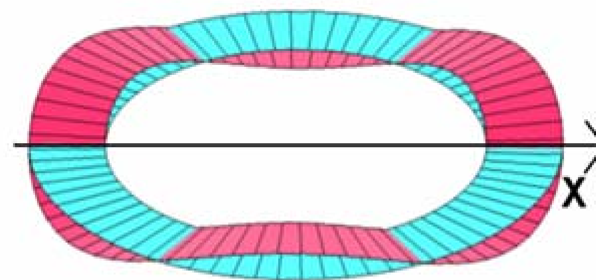
$\cos 2\phi$:driven



$\sin 2\phi : \Omega_z$



$\cos 3\phi : \Omega_y$



$\sin 3\phi : \Omega_x$

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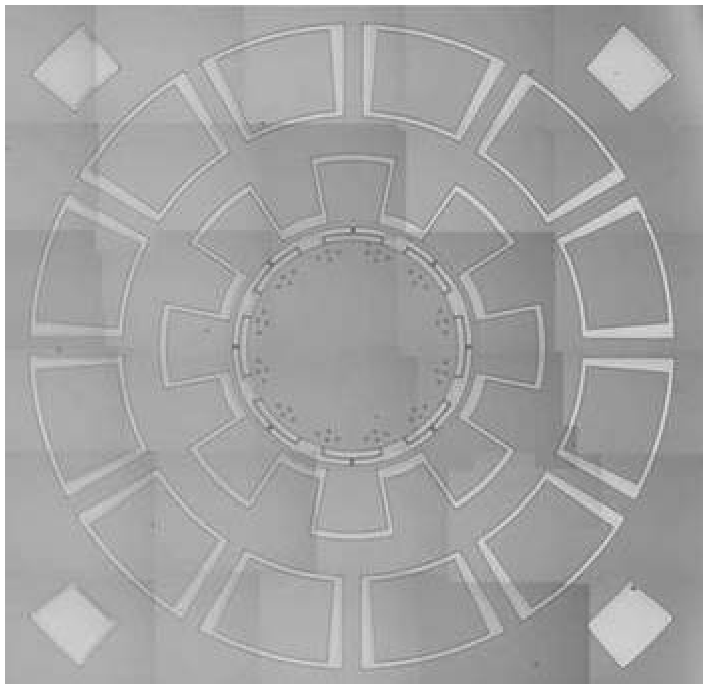

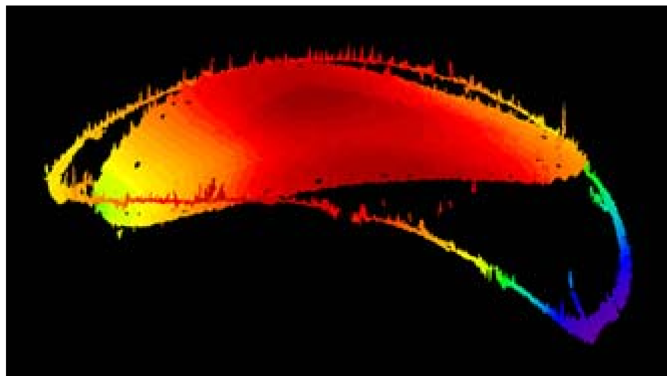

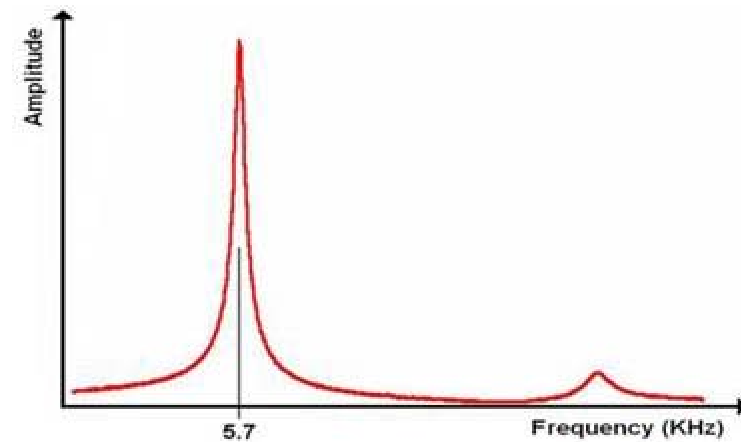

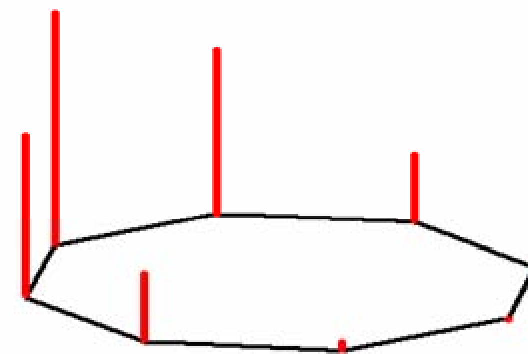

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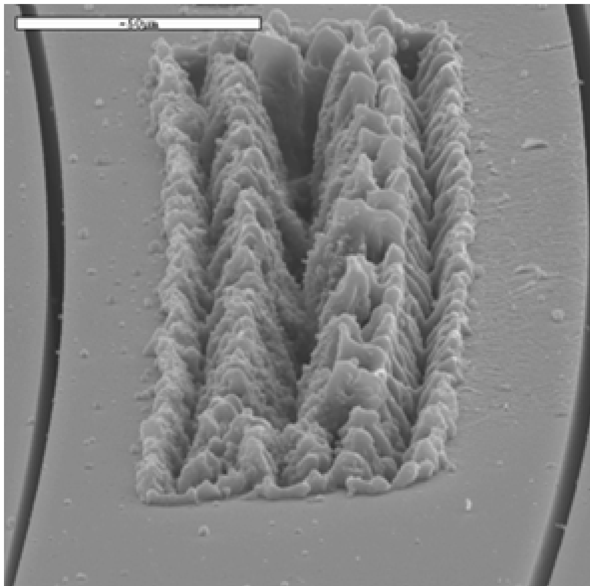
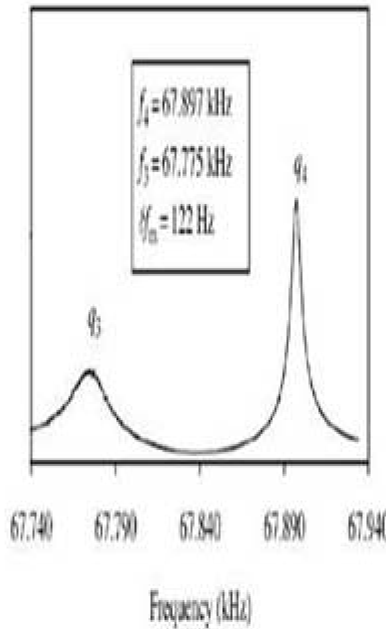
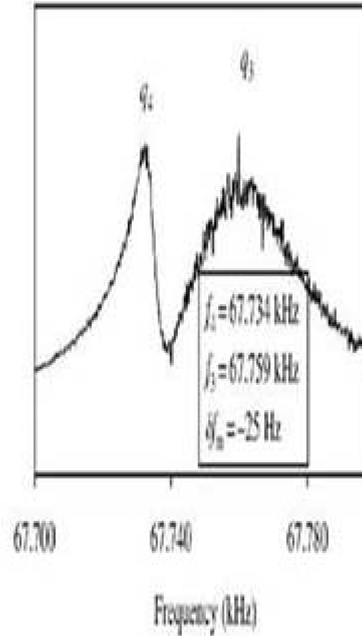
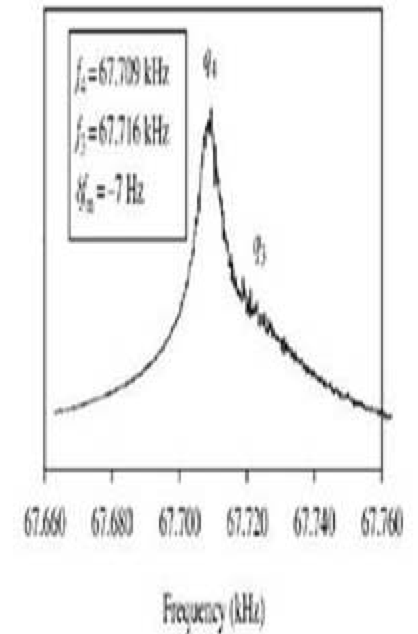
Passive mode tuning









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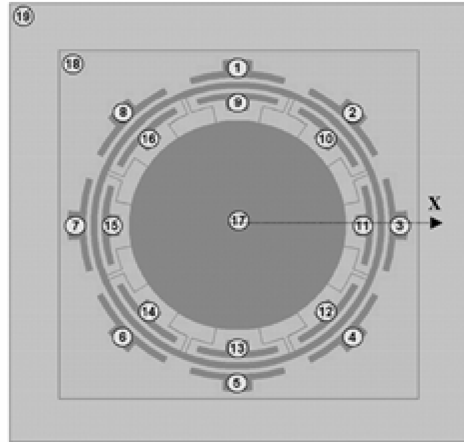
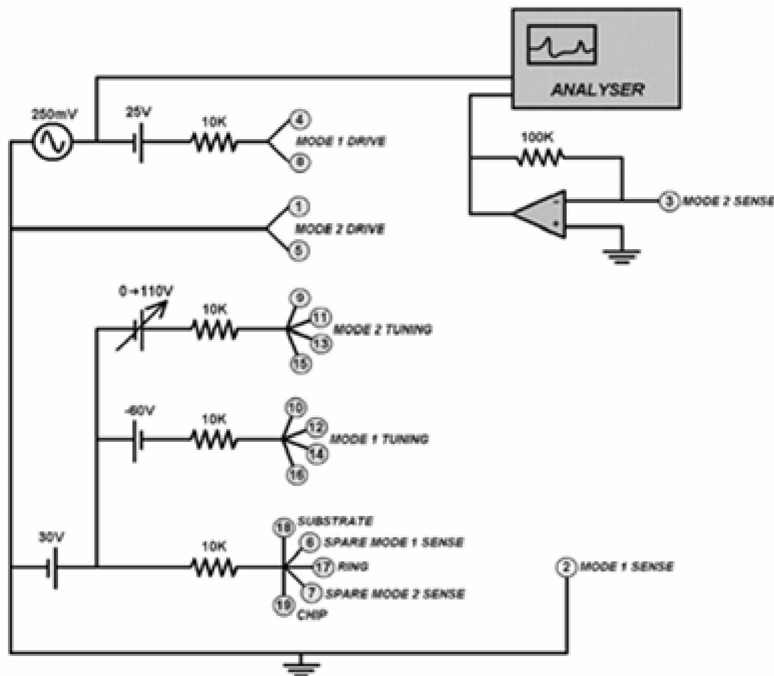
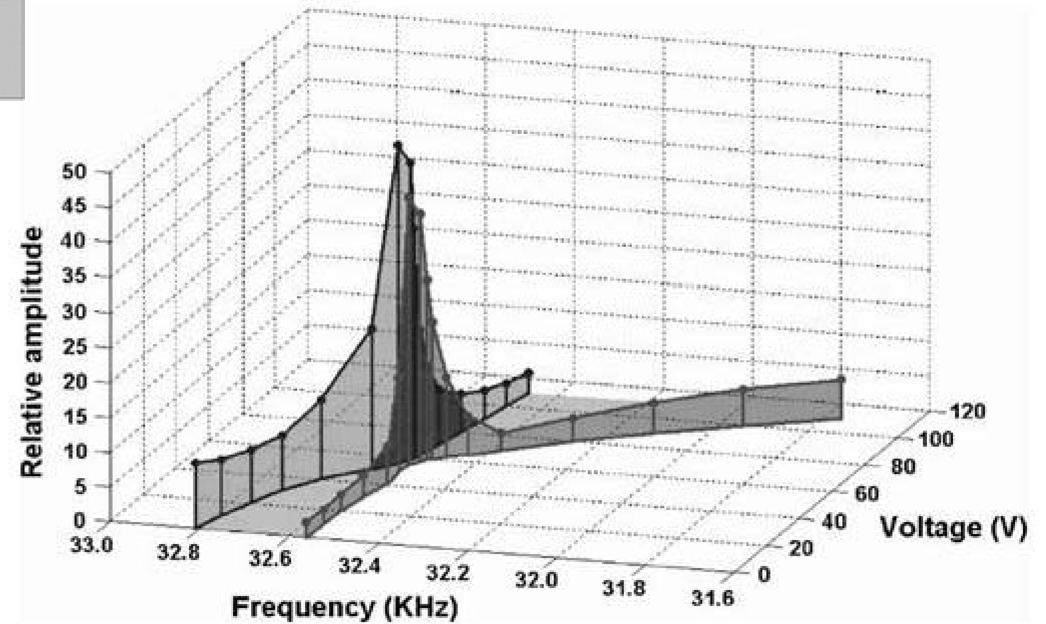
Active tuning







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Digital signal processing

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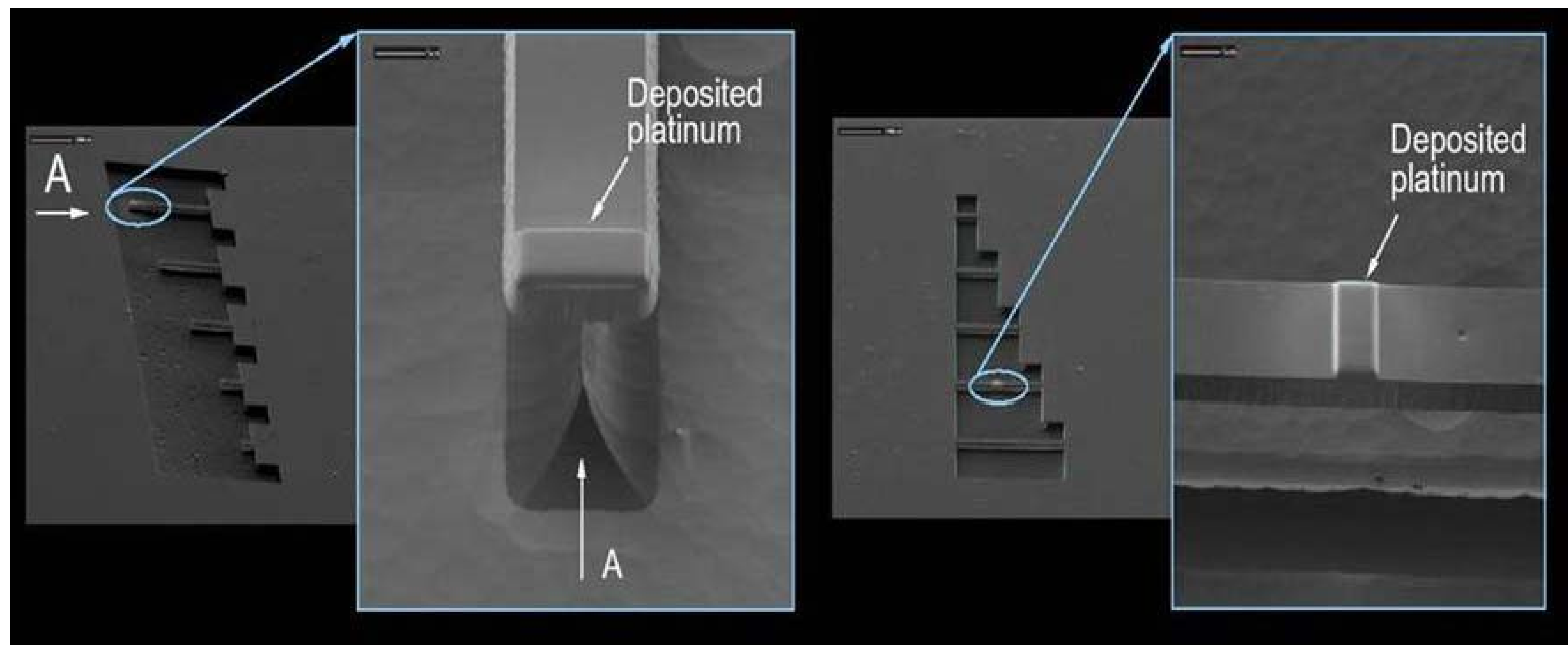
Ex. 2: FIB tuning (R. Cheung, Edinburgh)



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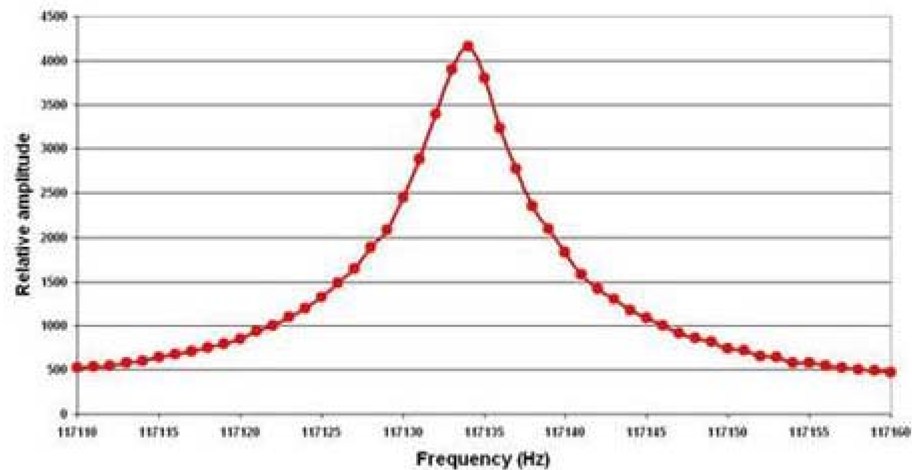
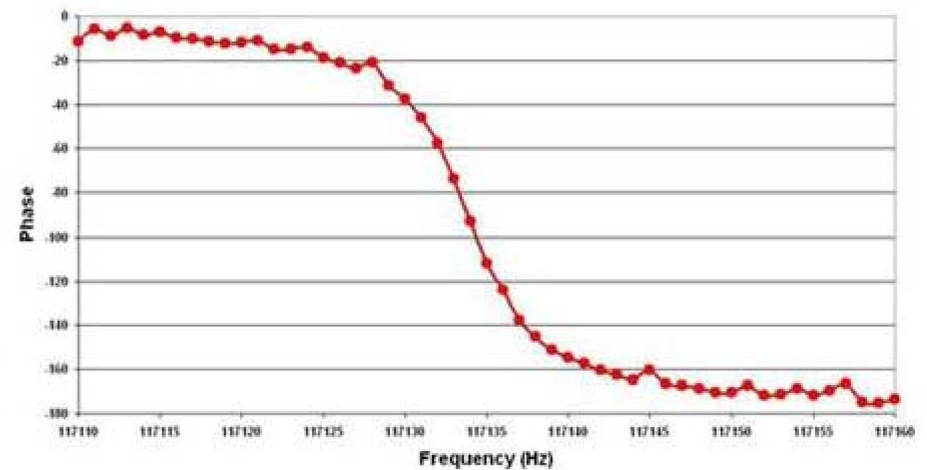
Cantilever frequency determination





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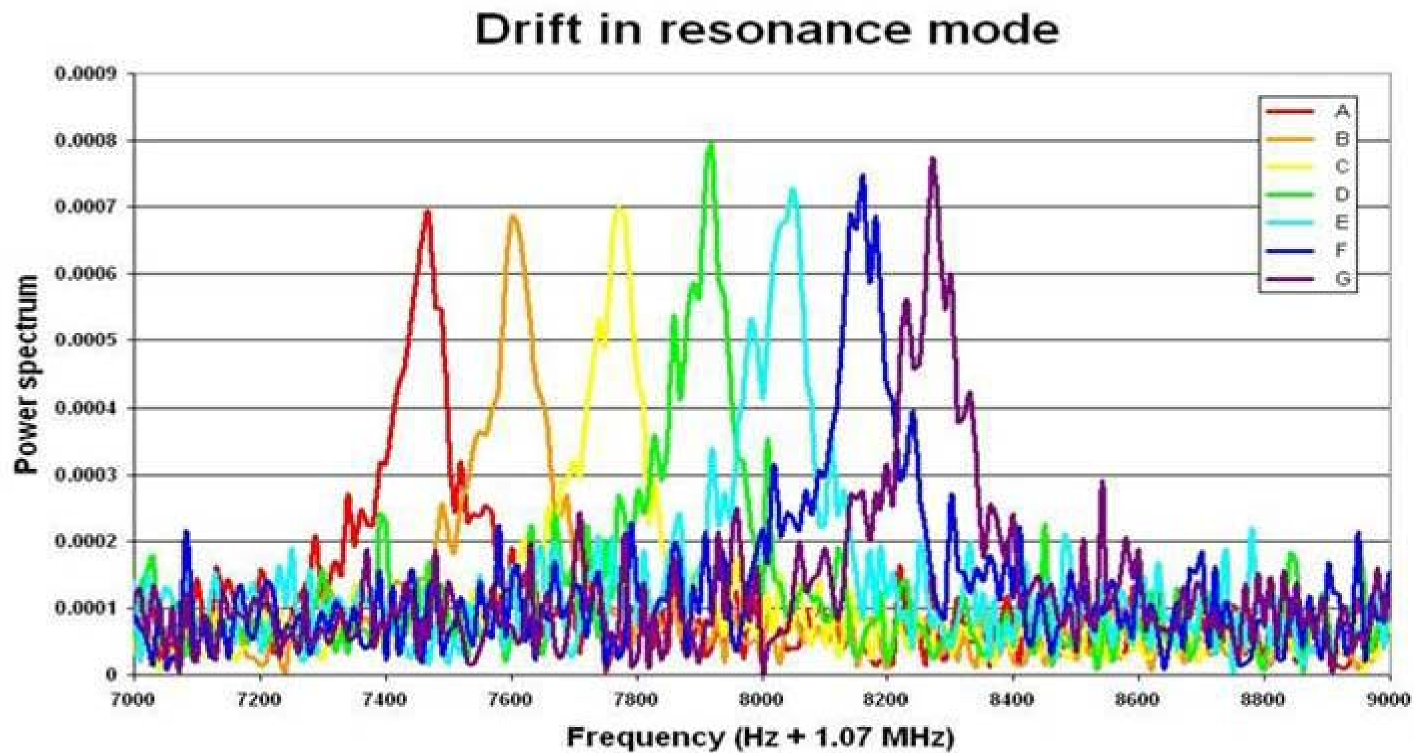
Bridge frequency determination



- Heating causes a drift in resonance frequency

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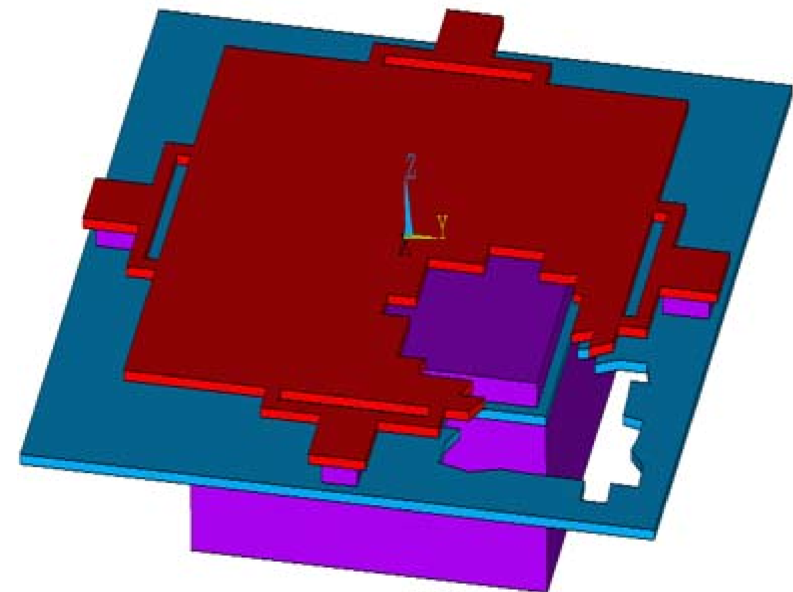
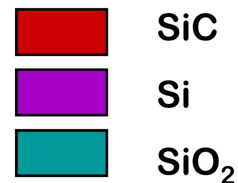
High temperature MEMS

- High temperature SiC devices and electronics
- Custom vacuum chamber developed for 800^{0}C measurements.





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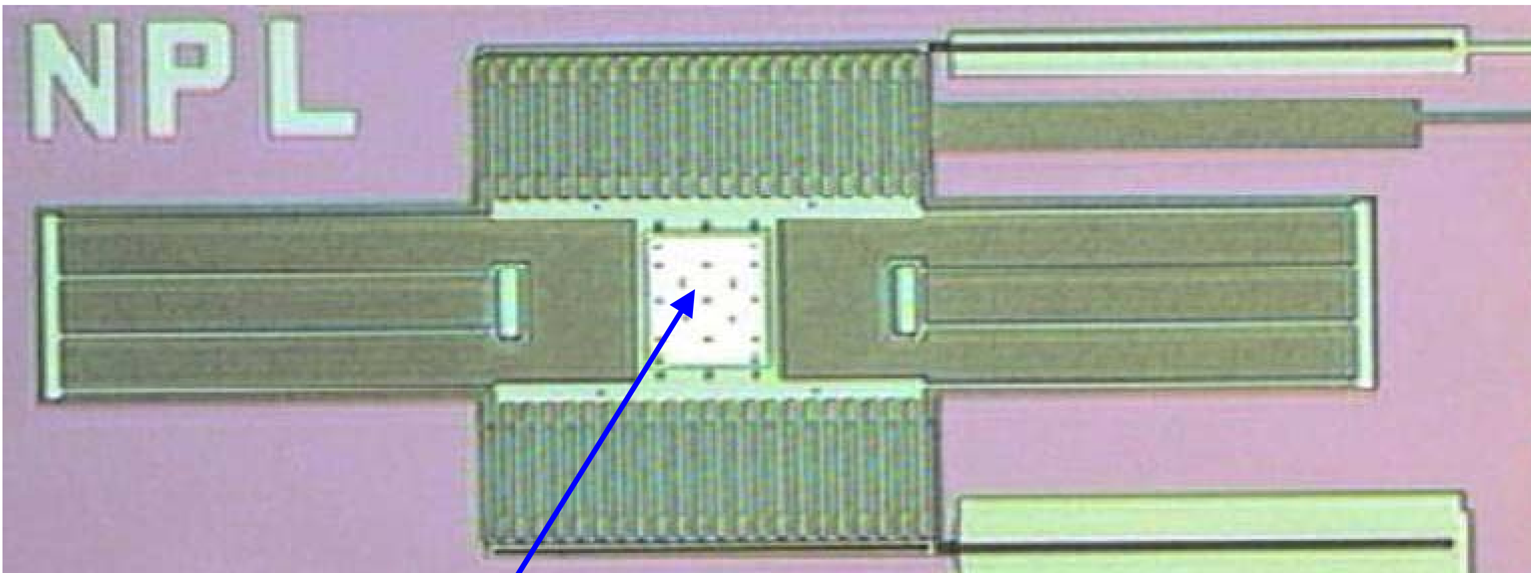
Ex. 3: AFM calibration (P. Cumpson, NPL)

- MEM device for AFM calibration



Gold pad to aid reflection.

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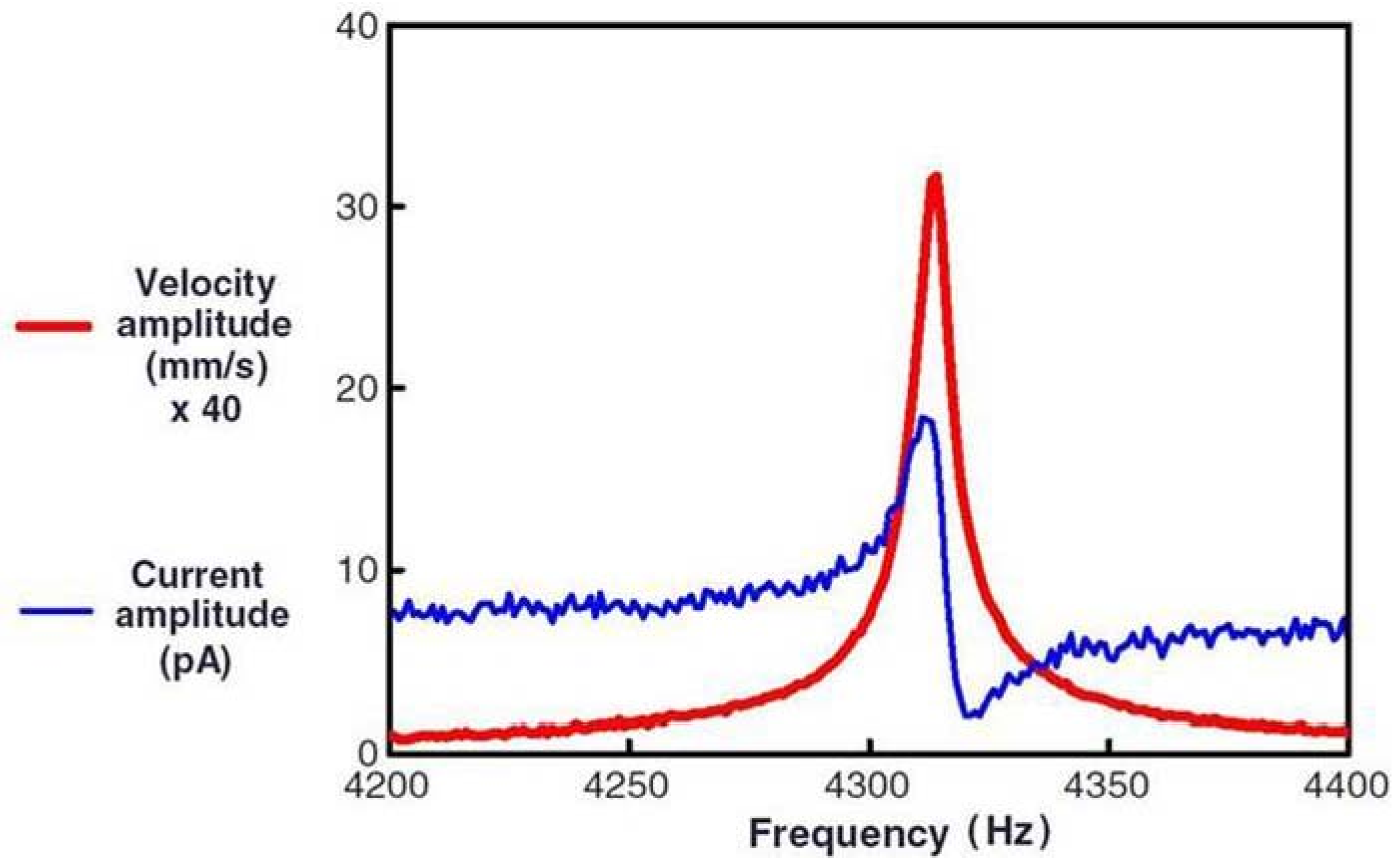
Dynamic characterization



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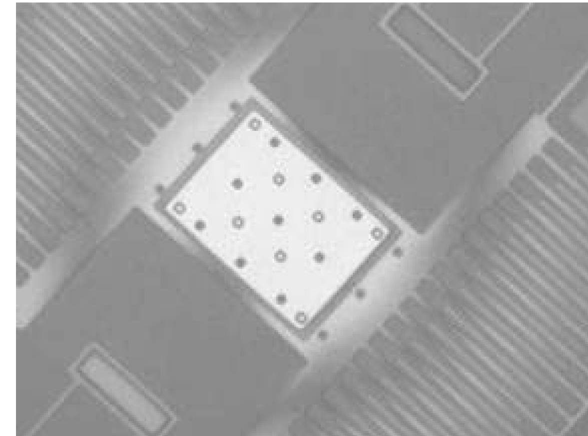
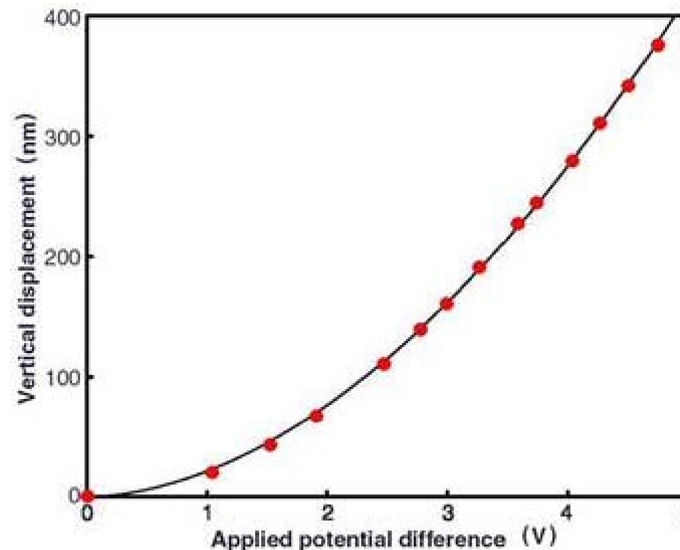
Static characterization

- Static deflections must be performed under vacuum.
- Compensated objective required (Linnik).
- Measured to 1nm resolution.





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Current capabilities

- Mounting and actuation options.
- Static measurements to 1um x 1um x 1nm.
- Dynamic measurements to 20 MHz and ~10 pm.
- Measurement issues resolved 'in situ'.

- Problem - spatial and dynamic limitations make MEMS and NEMS characterization a continuing problem.
- Possible solution – Raman spectroscopy

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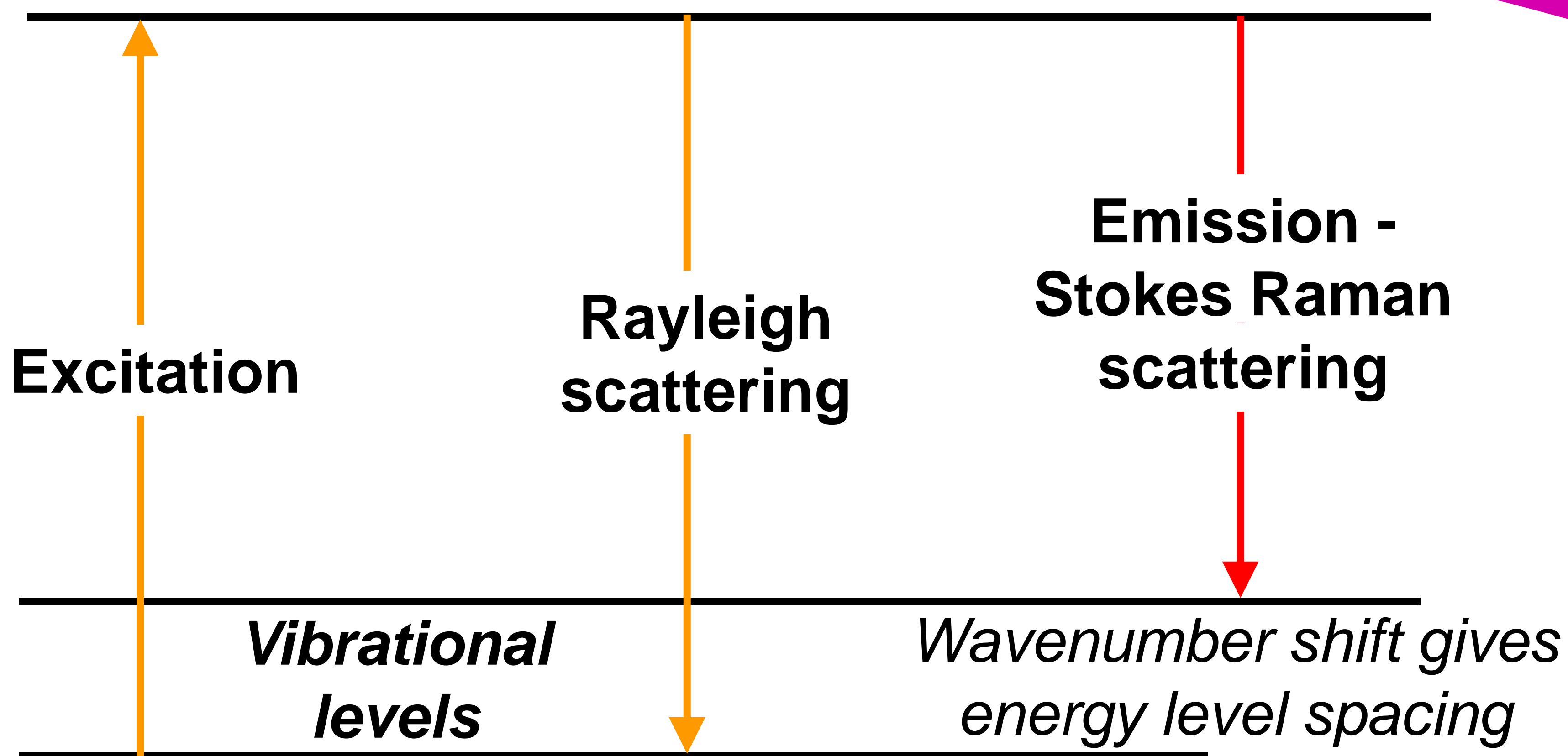
Raman spectroscopy



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Measuring strain

- Silicon gives a (triply degenerate) Raman peak at 520.8 cm^{-1}, strain in the silicon shifts this peak (lower wavenumbers when in tension).
- Shift in the Raman peak was shown to correspond to the volumetric strain in the unit cell [Anastassakis et al].
- A four point bending experiment [Bowden et al] determined this shift to be 5.2×10^{-4} cm^{-1} per volumetric μstrain (TO_z photon).
- For dynamic experiments, require either strobed measurement [Xue et al] or continuous (averaged) measurement.

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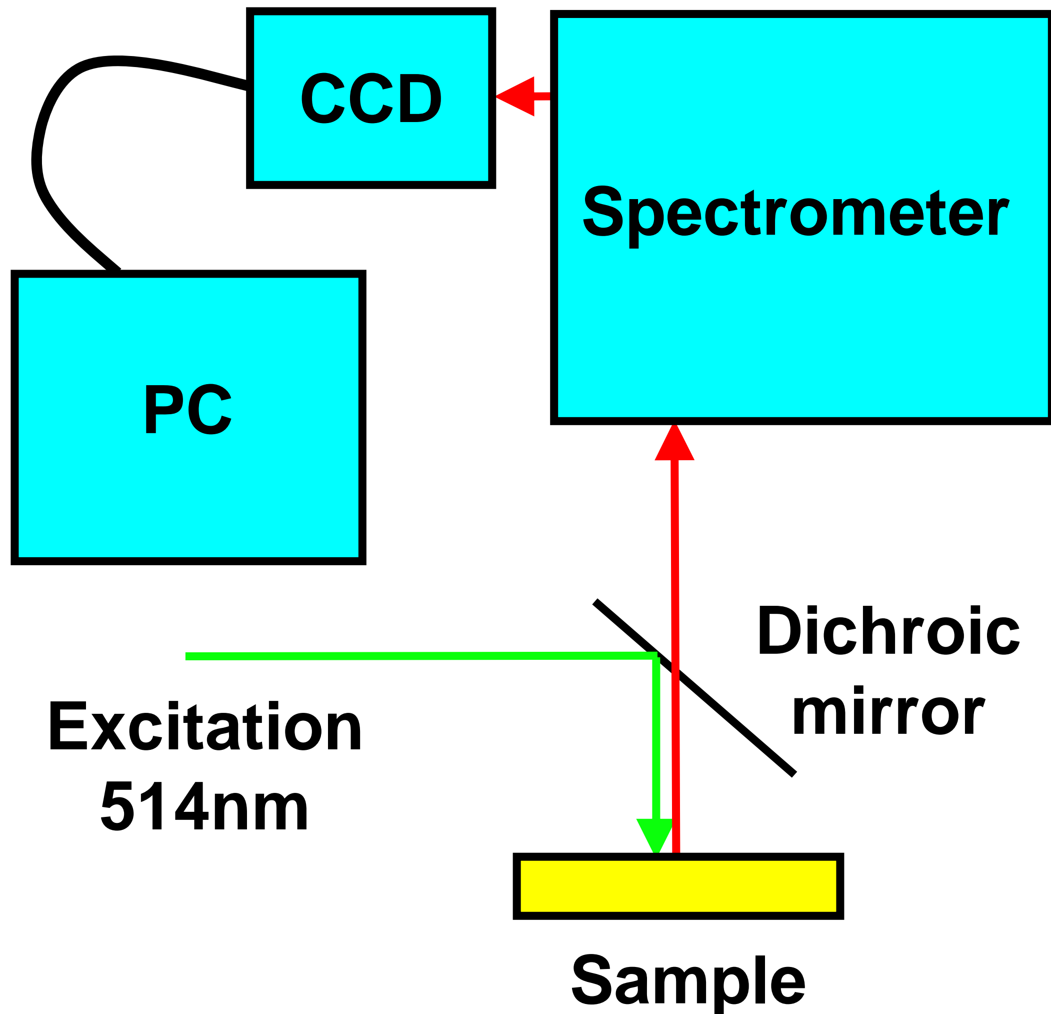
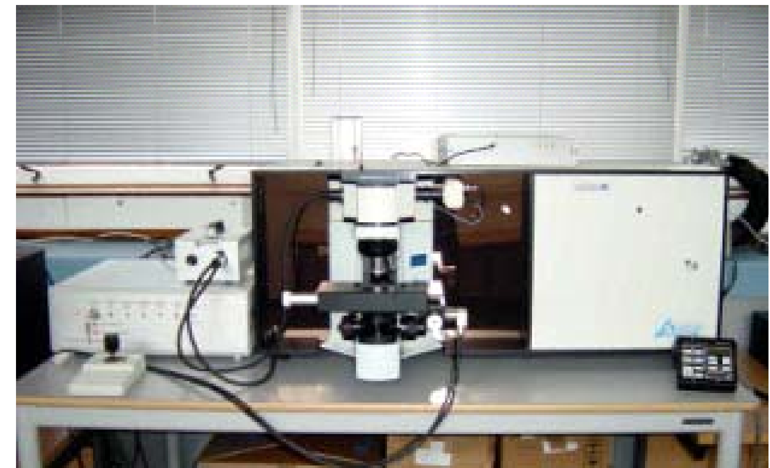
Raman equipment





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Experimental geometry

- Raman tensors, R_j, are [Loudon]:

$$TO_x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d \\ 0 & d & 0 \end{pmatrix}, \ TO_y = \begin{pmatrix} 0 & 0 & d \\ 0 & 0 & 0 \\ d & 0 & 0 \end{pmatrix}, \ LO_z = \begin{pmatrix} 0 & d & 0 \\ d & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- For incident and scattered polarizations, p_i and p_s, Raman intensity given by:

$$I = \left| p_s R_j p_i \right|^2$$

- For geometry here (<100>, 0^0 incident, 180^0 scattered), only TO_z photon observed.

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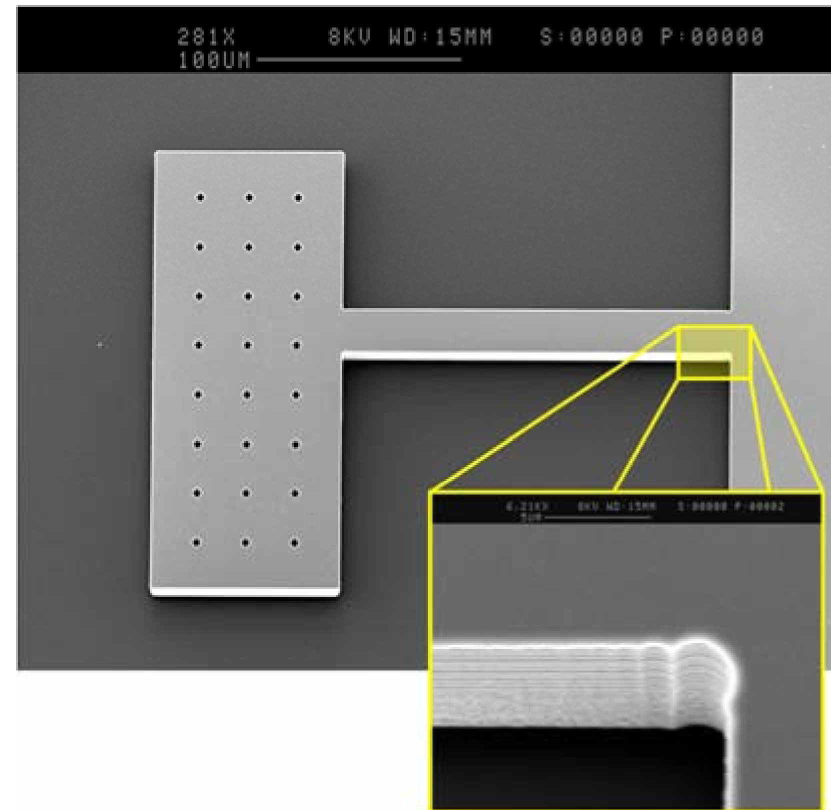
Test structures

- Simple <100> SOI test structures
- Beam section is 200x20x16 μm
- Easily actuated
  - in-plane
  - out-of-plane
  - twisting



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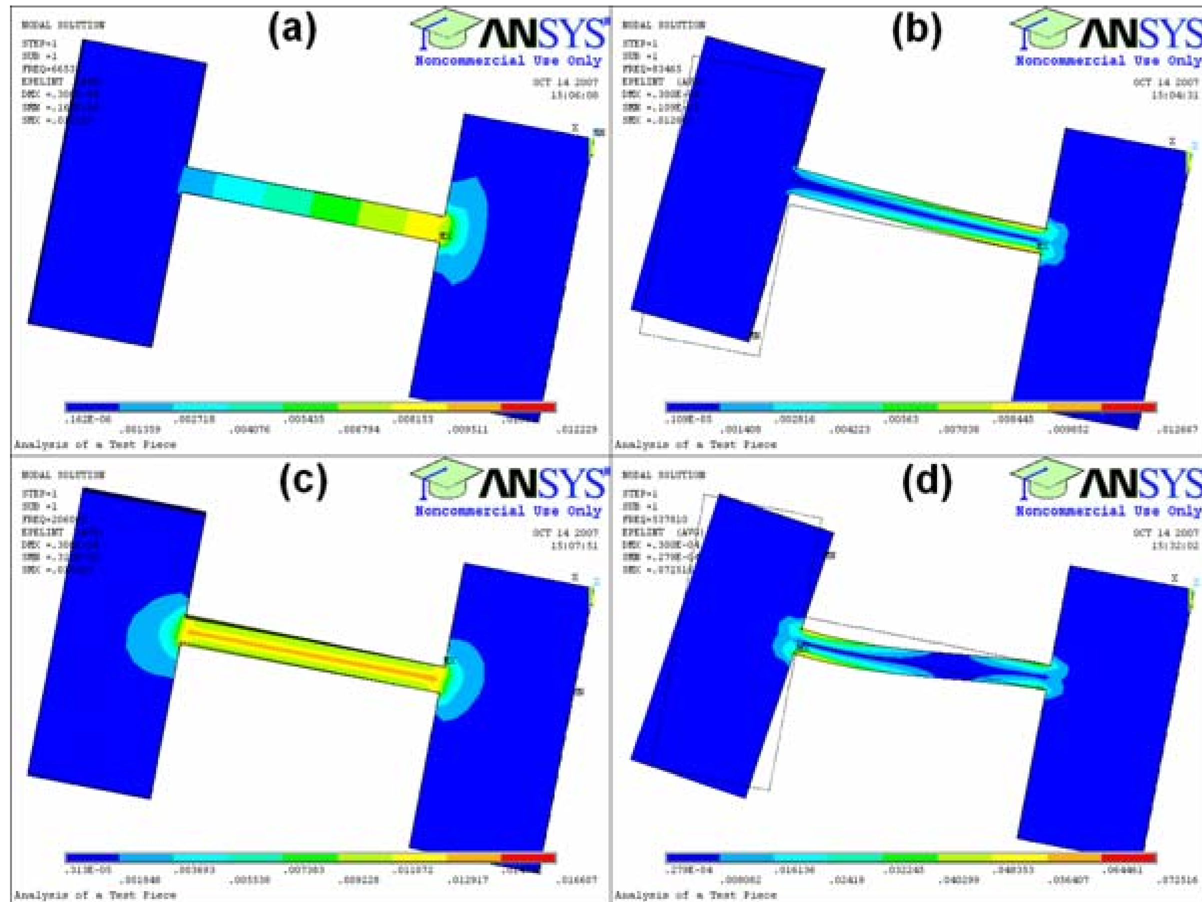
Modelling - strain indicates mode shape



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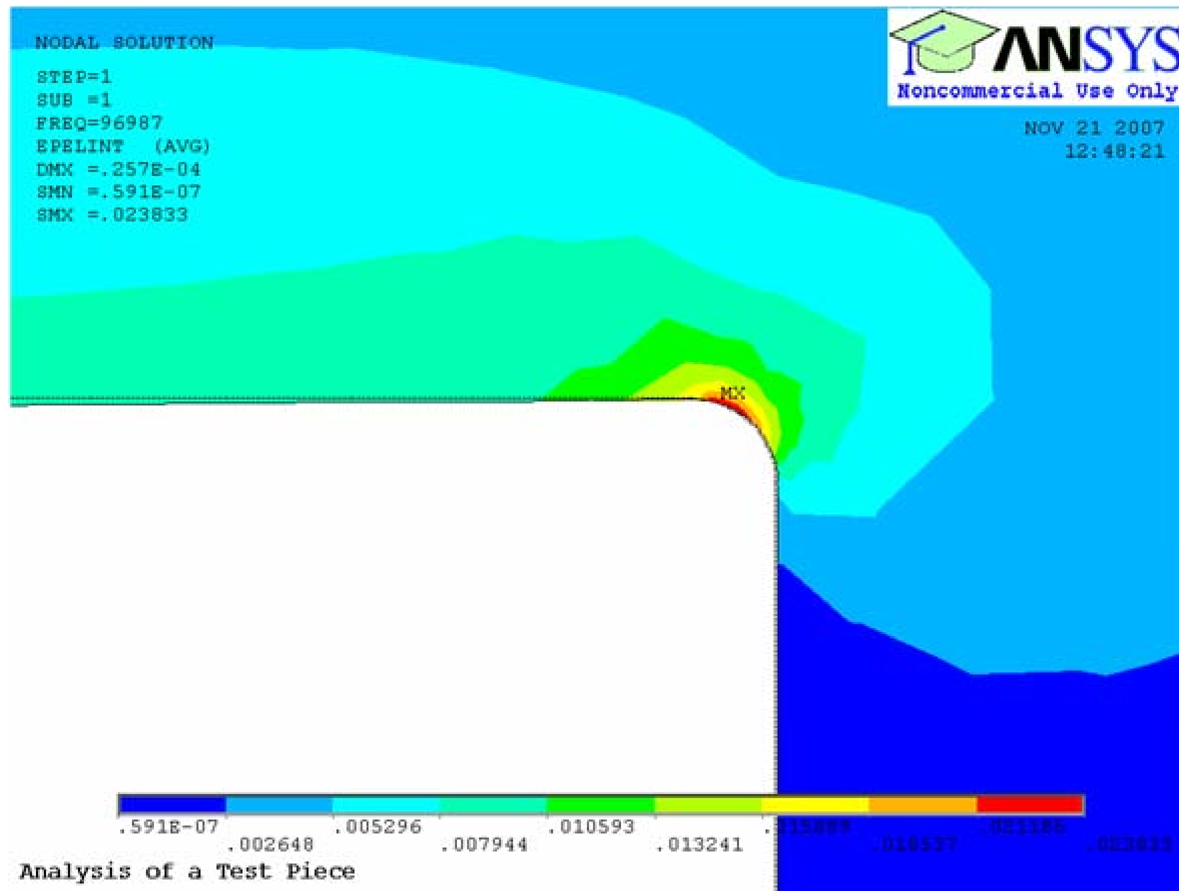
Modelling of strain concentration



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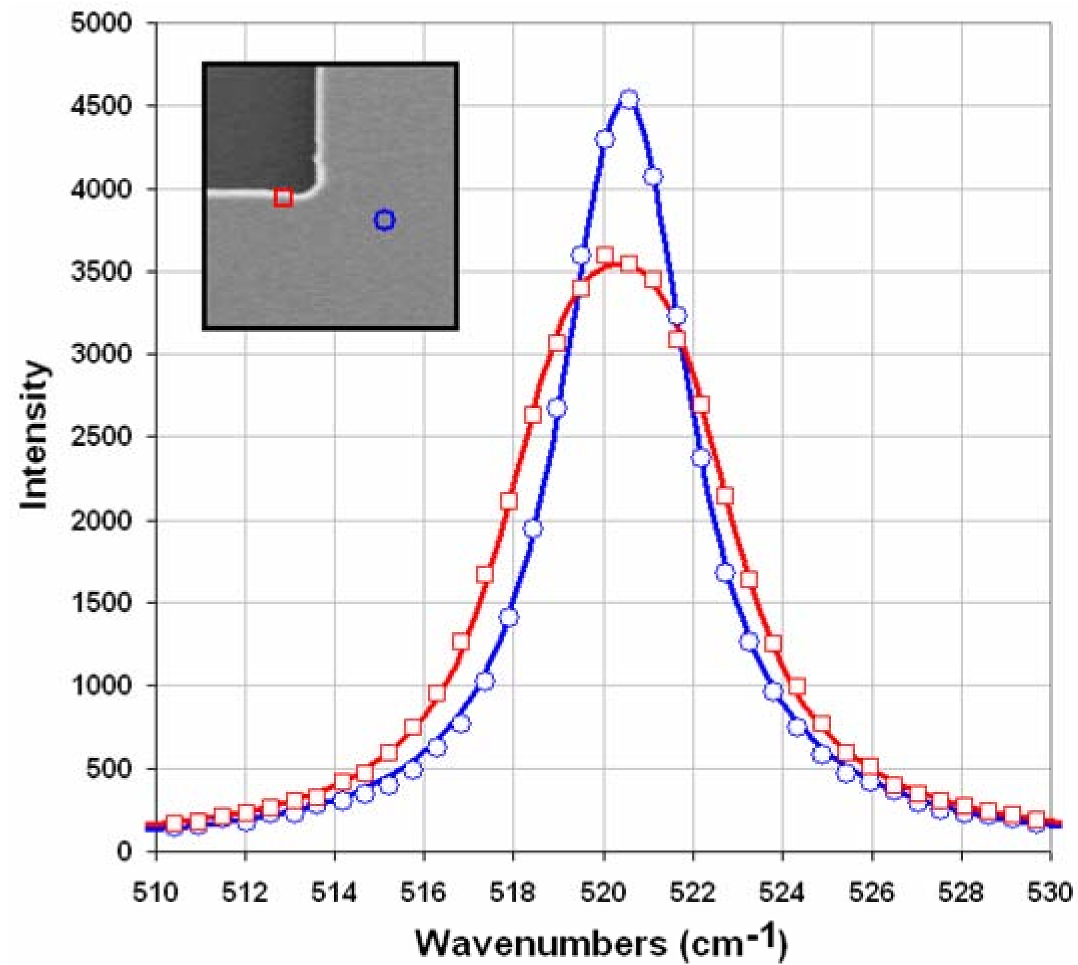
Typical spectra



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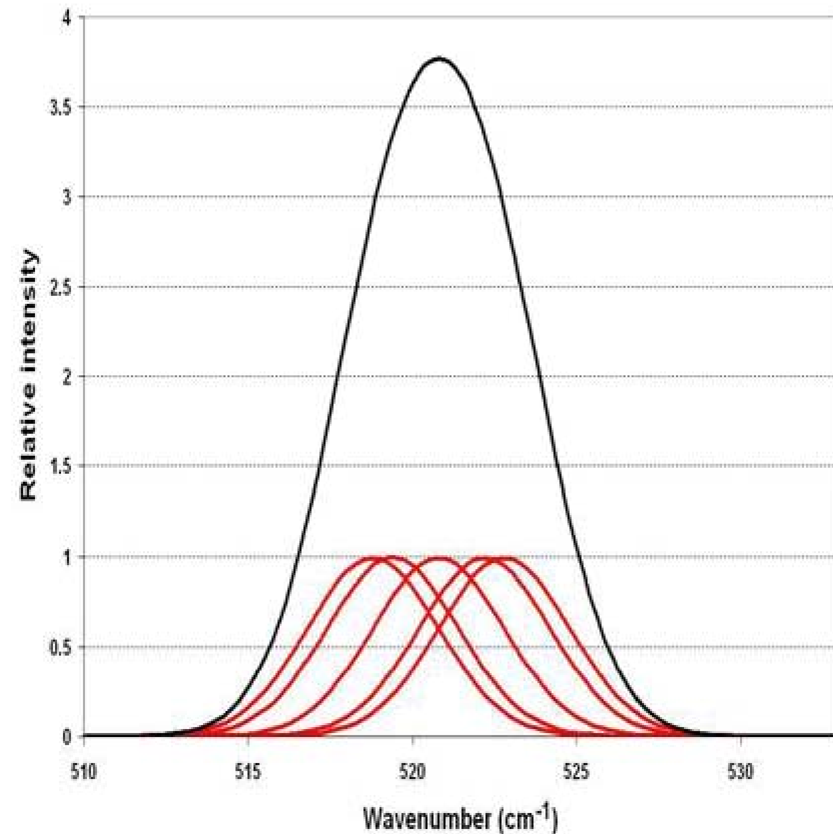
Fitting the spectra

- Voigt profile determined from static measurement.
- Sum of a spread of Voigt profiles, $V(\upsilon_0)$, gives overall profile, P:

$$P = \sum_{\theta=0}^{2\pi} V(A \sin \theta)$$

- *'A'* is amplitude of spread and found using Matlab fitting routine.



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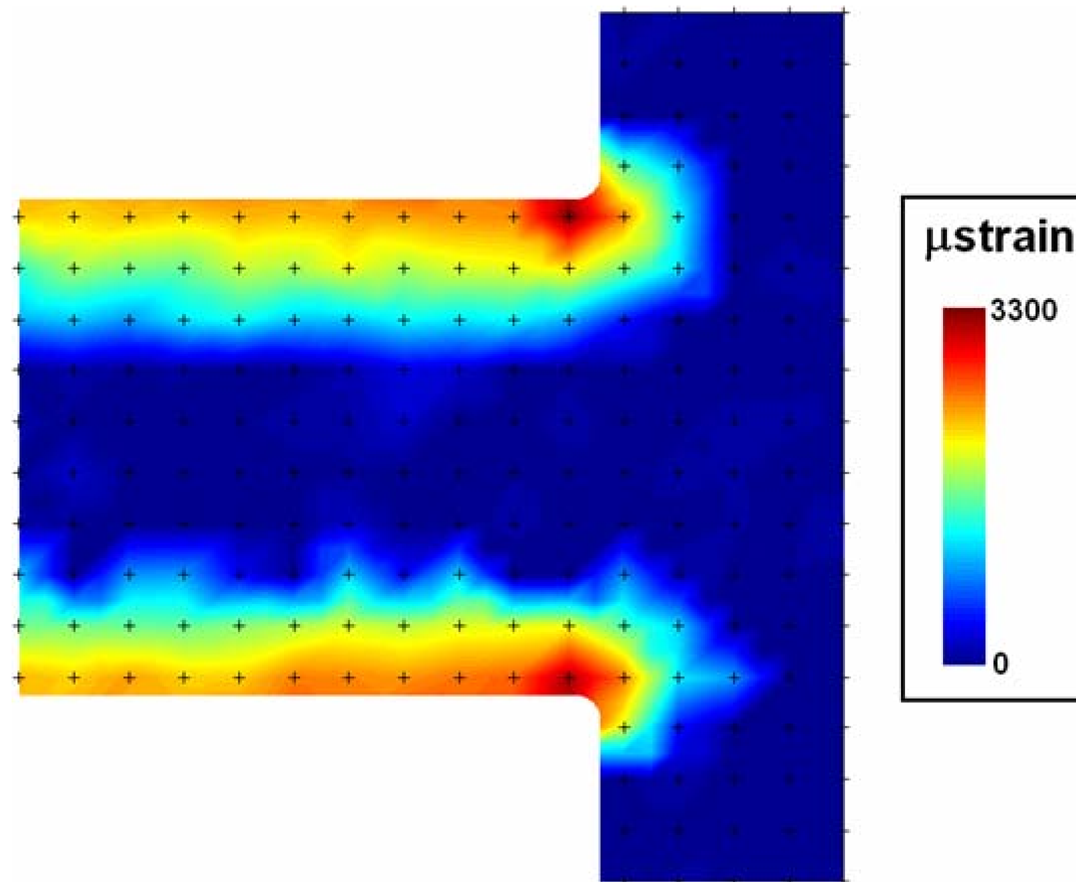
Measured strain map indicating mode shape



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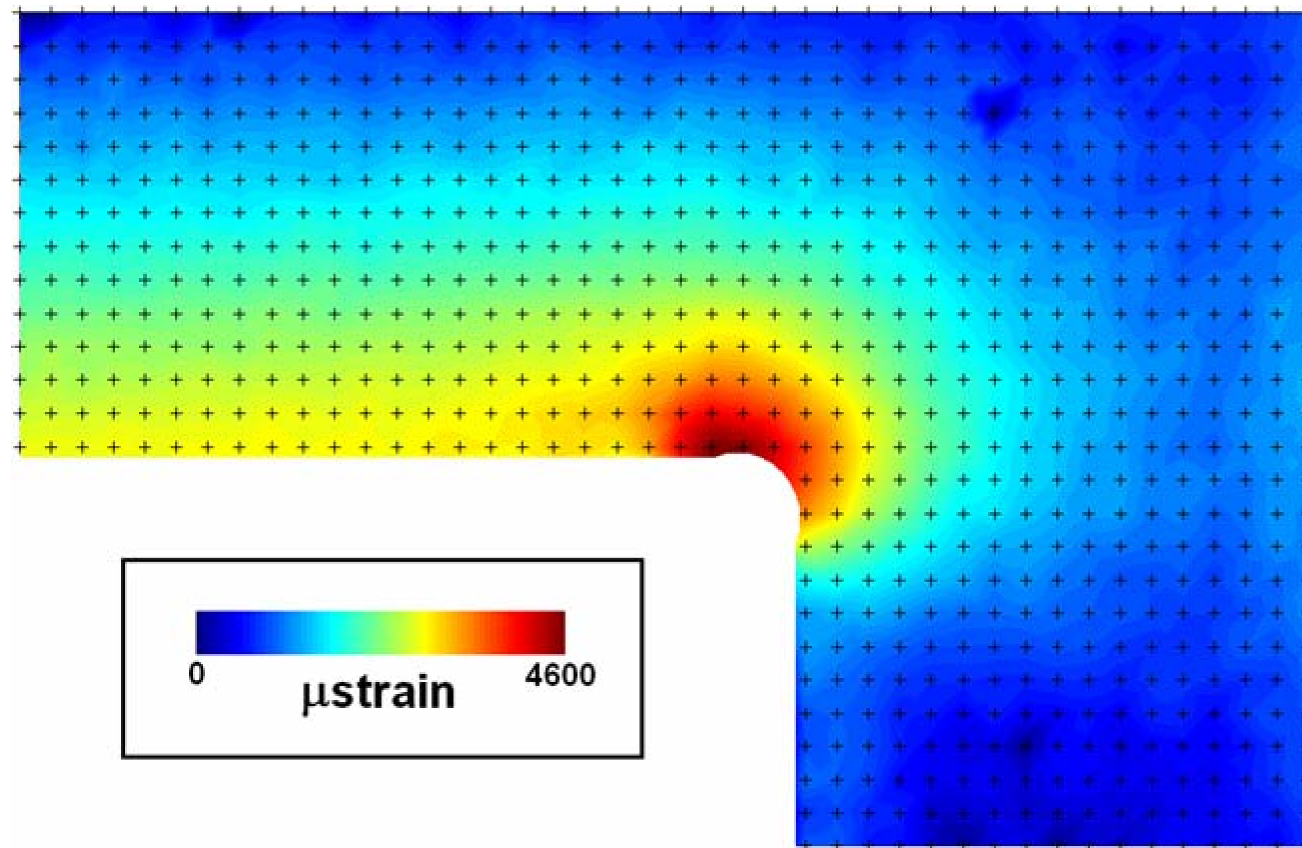
Measured strain concentration around fillet



Comparison of results

Technique	Freq. (KHz)	Vol. strain (µstrain)	Comments
FEA	97.0	8620 ± 780	Maximum
		5360 ± 490	1 μm^2 average
Expt.	101.3	4580 ± 30	1 µm spot diameter

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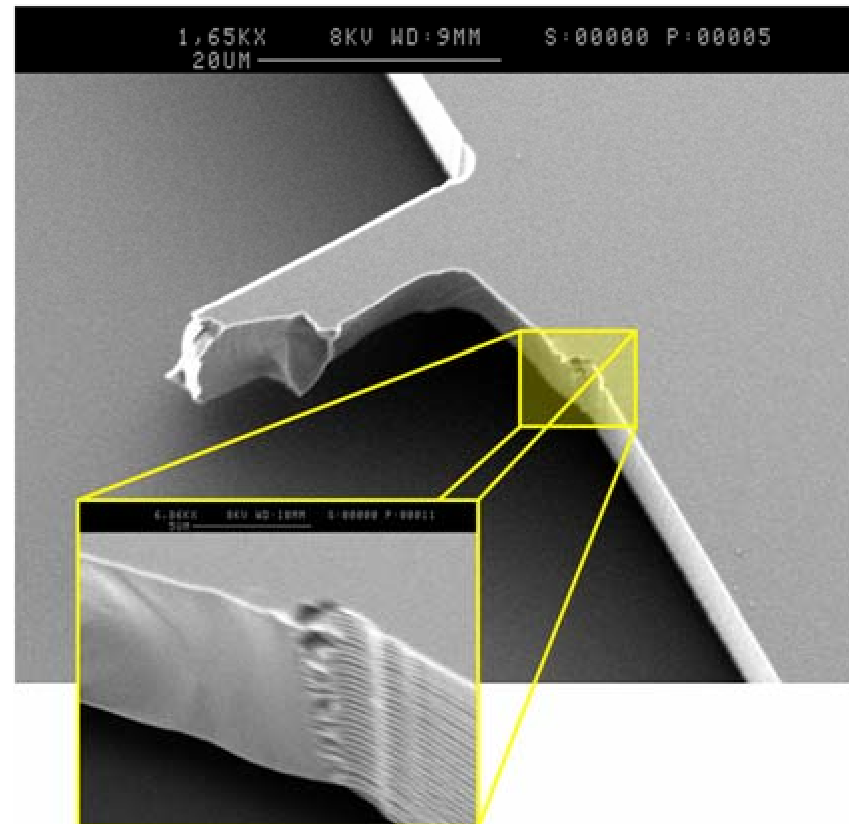
Failure prediction

- Overdrive device to induce failure
- Crack initiates from high strain location
- Possible application to reliability studies



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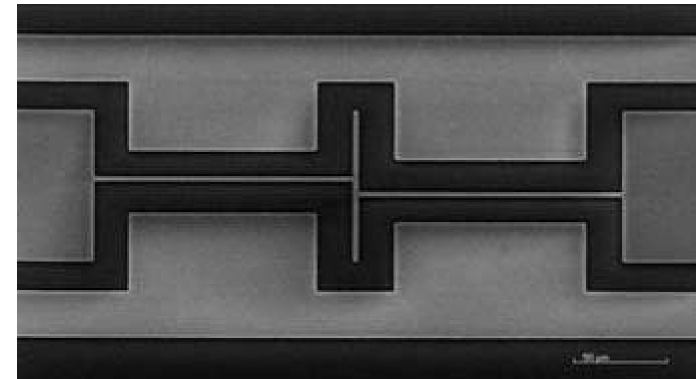
Modelling material properties in NEMS (B. Gallacher)

- Measure stress in Cu interconnect to aid IC reliability engineering
  - Static sensors
  - Dynamics sensors
- Investigating relaxation mechanisms in nanoscale thin films
- Using Off Lattice Kinetic Monte Carlo to determine critical thicknesses for:
  - Cracking
  - Dislocation



Static device for Al

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Summary - comparison of methods

Technique	Resolution	Range	Advantages
Profilometry	1nm	Static to <10 MHz	Large area
Vibrometry	10pm	10Hz to 20 MHz	FFT to determine all modes
Raman	30µstrain	Unlimited	UHF and potentially high spatial resolution

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Personnel

- Mechanical Engineering:
  - Jim Burdess, John Hedley, Barry Gallacher
  - Zhongxu Hu, Michele Pozzi
- Electrical Engineering:
  - Alun Harris, Jeff Neasham

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