Optical Measurement Techniques for MEMS Characterization

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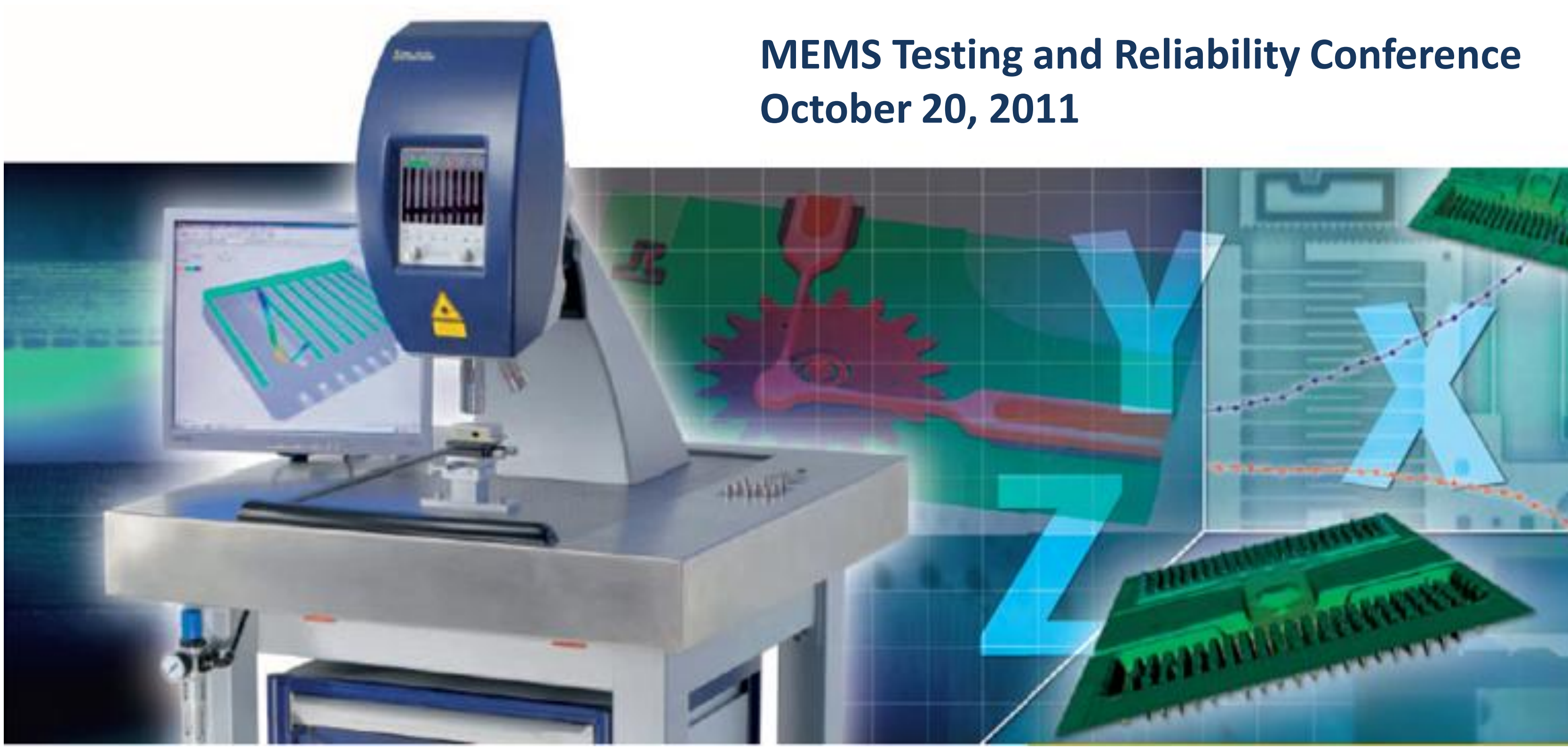
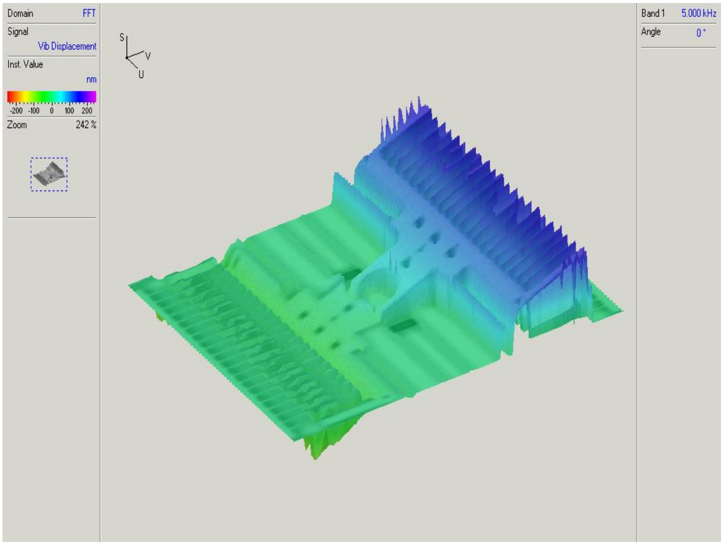
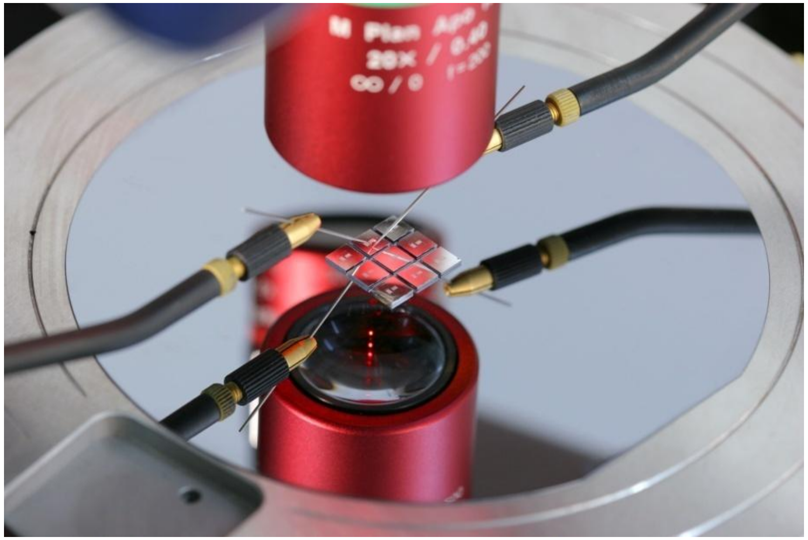


Motivation

Why optical characterization of MEMS?

- MEMS involve small, active elements for sensing and actuation
- Electrical test can prove if a device is working or not, but……
- Electrical testing can't determine exact physical characteristics
- →Need non-invasive optical measurement tools that are high resolution, precise and well-suited to diverse forms and functions of MEMS devices





Challenges and Requirements for MEMS Testing

- Diverse tools available to measure wide range physical properties (shape, dimension, film thickness, time response, stress, roughness, stiction, resonant frequency, environmental response…)
- High spatial resolution, accuracy and precision required
- Fast response times often require high speed measurement techniques
- Spatial complexity (mm – nm) of MEMS challenging for conventional techniques
- Wide range of performance criteria among different devices
- Handling and environmental requirements
- Fast measurement speed is critical for high volume production testing
- Reliable techniques that allow scientists and engineers to effectively communicate physical properties

MEMS Measurement Systems

- Optical Microscopy (OM)
- Strobe Video Microscopy (SVM)
- Atomic Force Microscopy (AFM)
- Scanning Electron Microscopy (SEM)
- White Light Interferometry (WLI)
- Confocal Microscopy (CM)
- Digital Holographic Microscopy (DHM)
- Laser Doppler Vibrometry(LDV)
- Other (Spectroscopy, Ellipsometry, ESPI, Light Scattering, Beam Deflection)

Typical Applications MEMS Measurements

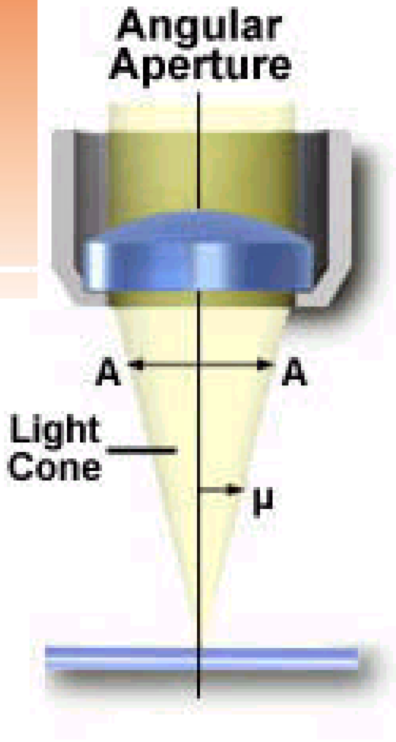
Stage	Typical Application	Technique
Material Property	Modulus elasticity of cantilever	**LDV** (Laser Doppler Vibrometry)
Material Property	Deformation of cantilever during mechanical or thermal loading	**DHM** (Digital Holographic Microscopy)
Fabrication	Etch parameters (shape and dimension)	**OM** (Optical Microscopy)
Fabrication	3D shape (step height, depth, curvature)	**CM** (Confocal Microscopy)
Fabrication	Static deformation of pressure sensor	**WLI** (White Light Interometer)
Fabrication	Surface roughness of RF switch	**AFM** (Atomic Force Microscopy)
Fabrication	Oxide layer uniformity and cross section	**SEM** (Scanning Electron Microscope)
Performance	Static tilt angle of μmirror	**WLI** (White Light Interometer)
Performance	Visualization of settling time response μmirror array	**LDV** (Laser Doppler Vibrometry)
Performance	Step response comb drive actuator	**SVM** (Strobe Video Microscopy)
Environmental	Crack propagation from thermal loading	**SEM** (Scanning Electron Microscope)

Optical Microscopy (OM)

- Fast **visual examination** of visible defects
- Highly suited of fabrication process
  - Presence verification
  - Position recognition
  - Geometric features
  - Surface flaws (cracks, scratches)
- Rapid Computer Vision techniques for digital image processing and analysis
- Wide choice of lens available for required resolution, field of view, focal depth, stand off distance
- **Lateral resolution**: sub-micron - diffraction limited:

$$(d = (1.22 / 2NA) \times \lambda)$$

- Limited height resolution



- **<u>Limitations</u>**:
  - Static images – no topography or dynamic response measurements
  - Limited to optical scale (microns)

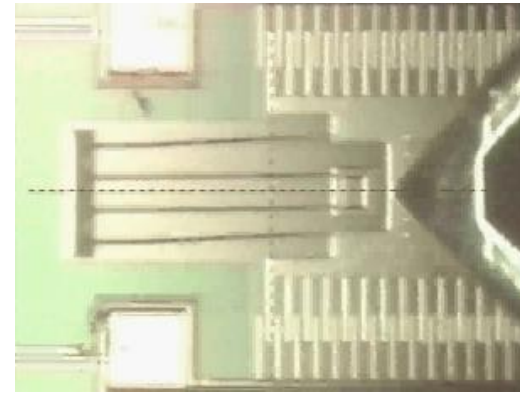
Optical Microscopy (OM)

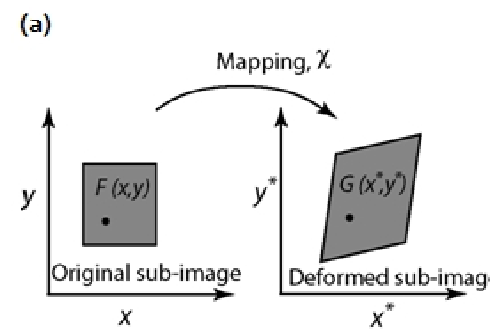
•**<u>Imaging Techniques:</u>**

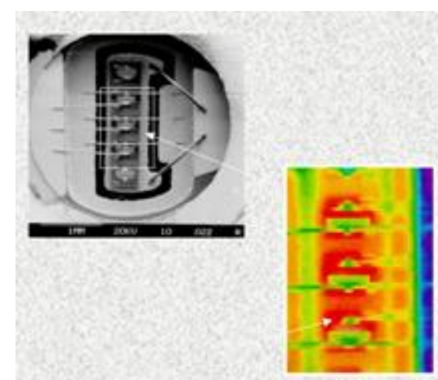
•**High Speed Video** to see real-time dynamic response over whole field of view

•**Digital Image Correlation (DIC)** to evaluate changes during thermo-mechanical process (deformation, displacement, strain, fracture, alignment)
•Pattern matching with sub-pixel resolution of localized feature (kernel) during loading process
•Available analysis software is simple and easy to use.
• Interfaces w/ Finite Element Analysis (FEA)software
•Method has excellent scaling capabilities for use on:
    •smaller features with SEM
    •dynamic response w/ high speed or strobe video

•**Infrared Camera Imaging** to see thermal emission from active electrical junctions and friction

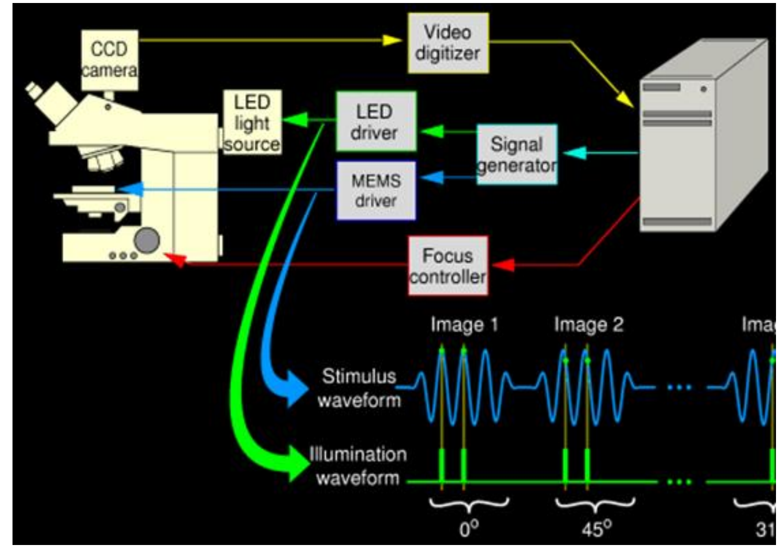


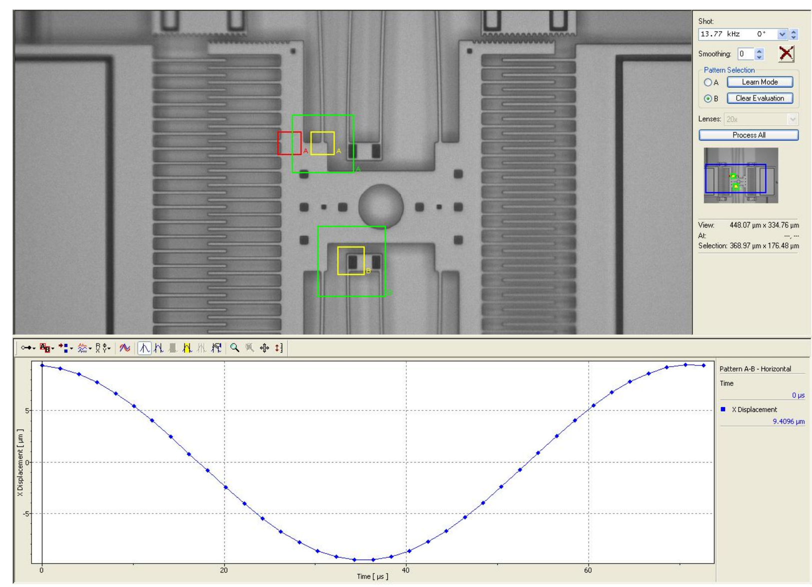




Strobe Video Microscopy (SVM)

- Stroboscopic imaging to capture **in-plane motion**
- Sequence of “frozen” images at different phases of movement
- Pattern matching tracks and measures movement
- Provides measurements of
    - Resonant frequency
    - Amplitude
    - Settling Time
- **Lateral Dynamic Resolution** : 0.01 μm
- Can be combined w/ LDV or White Light Interferometer to include vertical motion
- **Vertical Dynamic Resolution** (w/ WLI) : 0.01 μm

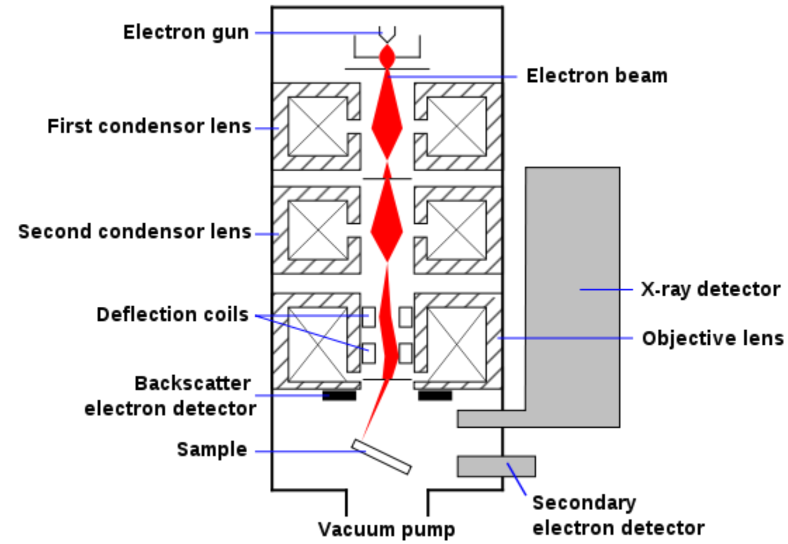




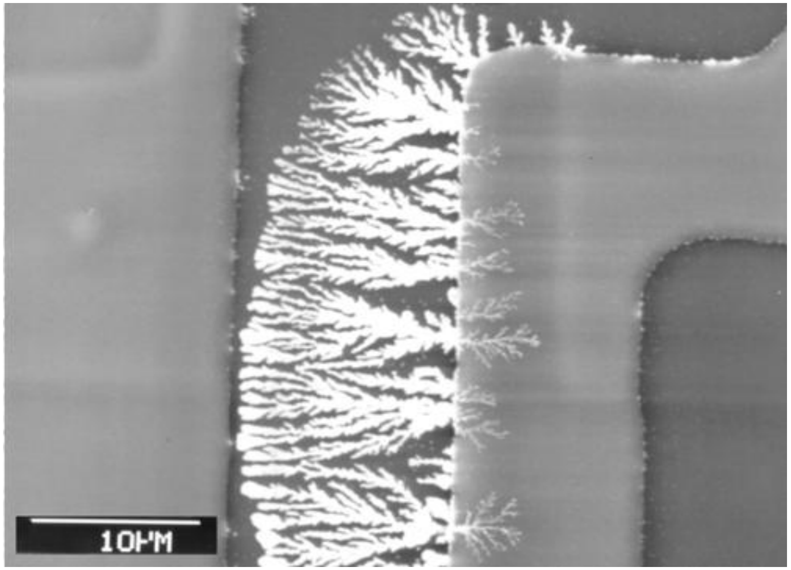
- **<u>Limitations</u>**:
    - Limited to in-plane response (unless WLI used)
    - Limited to repetitive motion (sine or step excitation) – no transient response
    - Not real-time measurement - slower measurement requiring post processing
    - Limited to nanometer level resolution

Scanning Electron Microscopy (SEM)

- **Very high resolution 2D images** (x250 better than microscope)
- Scans a focused beam of electrons over sample
- Images detected electrons scattered from surface
- Fast measurement times (5 – 10 seconds)
- Large depth of focus (3D appearance)
- Sidewall angles & roughness of steep parts
- Laboratory instrument to measure
  - Sub-microscopic surface features
  - Morphology and Compositional Information
- **Lateral Resolution**: <1 nm
- Can provide slow video of dynamic response



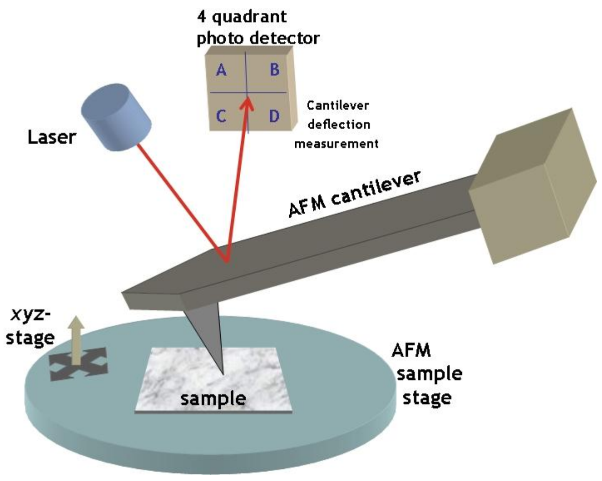
- **<u>Limitations</u>**:
  - Only 2D image of sample – no height values
  - Samples must be placed in a vacuum
  - Penetration depth of electrons small
  - Devices must be prepared and cross sections oriented for optimal measurements
  - Edge effects causing measurement artifacts

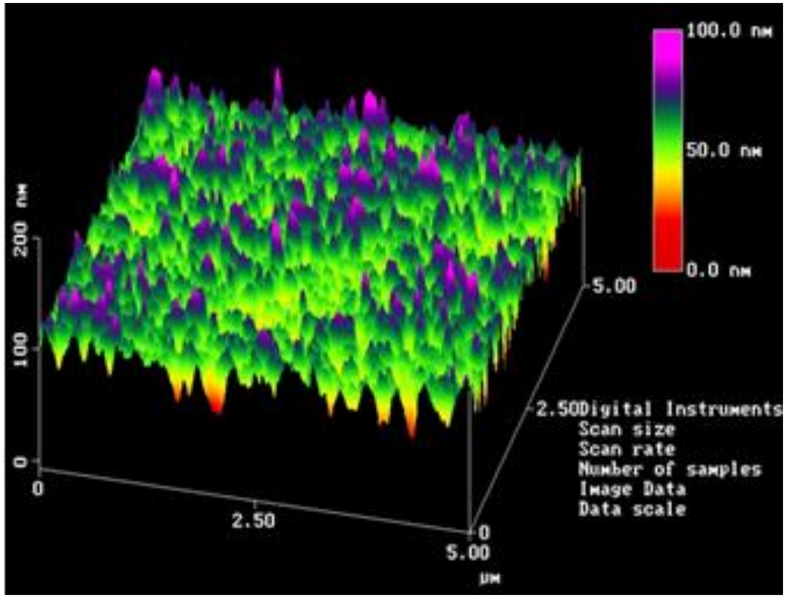


Atomic Force Microscopy (AFM)

• Very high resolution 3D images **surface topography** (over 1000 times better resolution than optical)
•Scanning probe microscope (not optical)
•"Tapping mode" measurements are non-contact
•Lab instrument to measure
  •Surface properties of material
  •Material properties
•Works well in ambient conditions & in liquid
•Variants for electrical properties (CAFM,EFM, TUNA)
•**Highest Lateral and Vertical resolution**: Angstrom

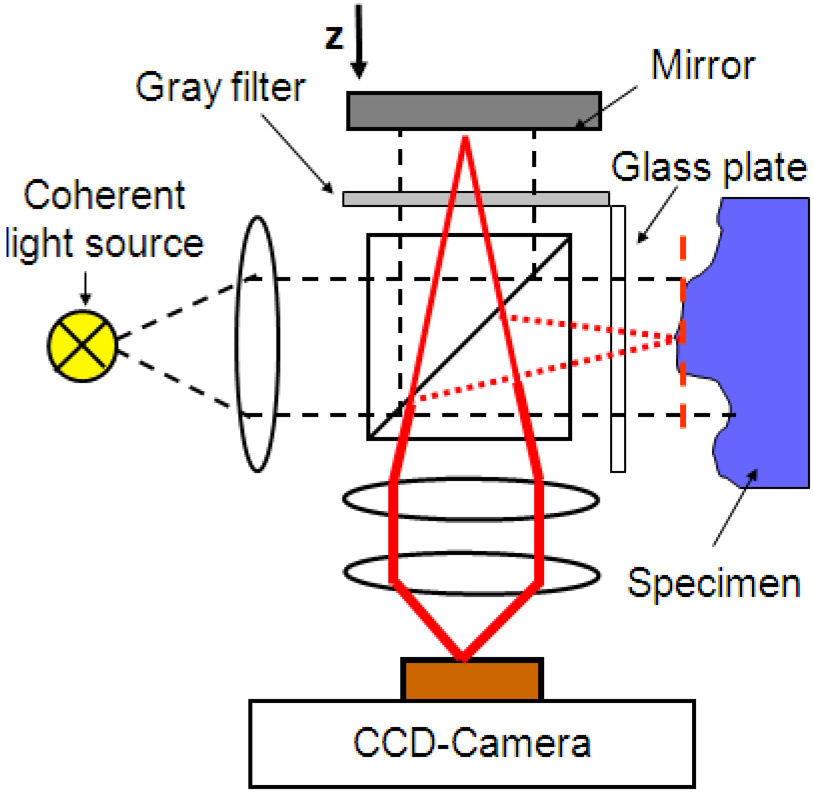
•**<u>Limitations</u>**:
  •Raster scan of AFM tip involves longer measurement times for hi res. 3D image
  •Maximum 20 μm height and 150^2 μm area
  •Difficulty on steep walls of material
  •Thermal drift effects accuracy
  •Artifacts when surfaces are non-homogenous
  •Hysteresis / cross talk can cause flattening
  •Can't measure thru glass (in vacuum chamber)



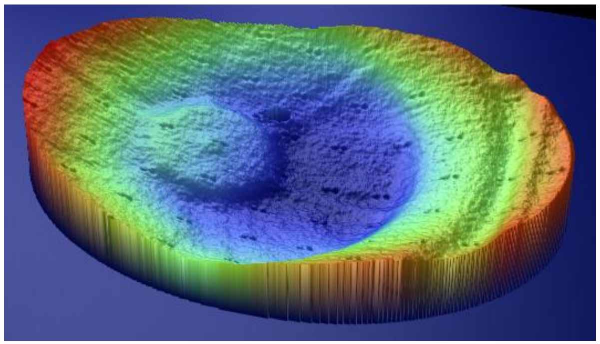


White Light Interferometry (WLI)

- Fast, full field measurements of **surface topography**
- Well suited for investigation of fabrication process
  - uniformity of etching and electrodepositing
  - stiction
  - film stress
  - delamination
  - roughness
- **Lateral resolution**: sub-micron
- **Vertical resolution**: nanometer (0.1 nm achievable)
- Dynamic response using strobe technique

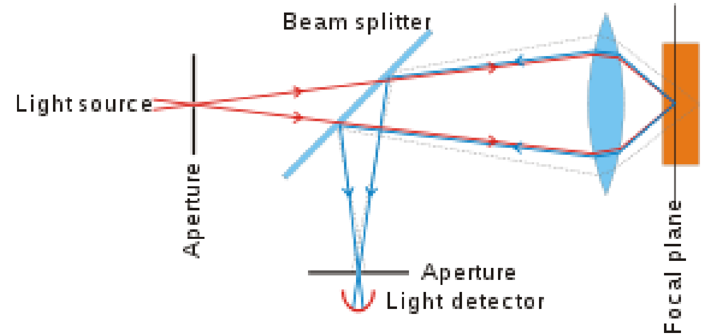


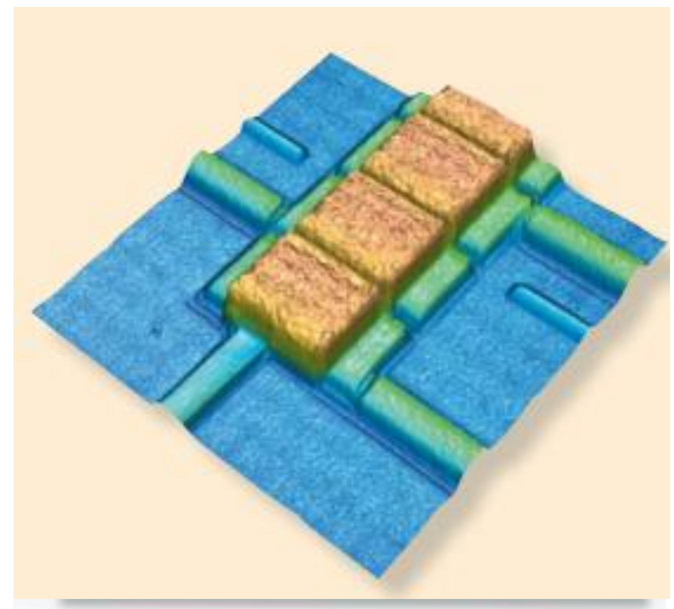
- **<u>Limitations</u>**:
  - High power light source needed
  - Best results uniform / reflective materials
  - Edge effects cause non-uniformities ("batwings")
  - Inhomogeneous materials cause height errors
  - Difficult to measure thru glass (i.e. into vacuum chamber)
  - Sensitive to vibration
  - Not real time – requires post processing



Confocal Microscopy

•Optical Imaging Technique for **3D imaging**
•Uses point illumination and spatial pinhole to eliminate out-of-focus light, increasing resolution and contrast
•Scanned over surface to map 3D image
•Less sensitive to vibration than interferometry
•Commercial instruments widely available
•Spinning disk (Nipkow) for hi speed video capture
•Laser scanning version hi resolution (bio applications)
•**Lateral resolution**: sub-micron
•**Vertical resolution**: nanometer





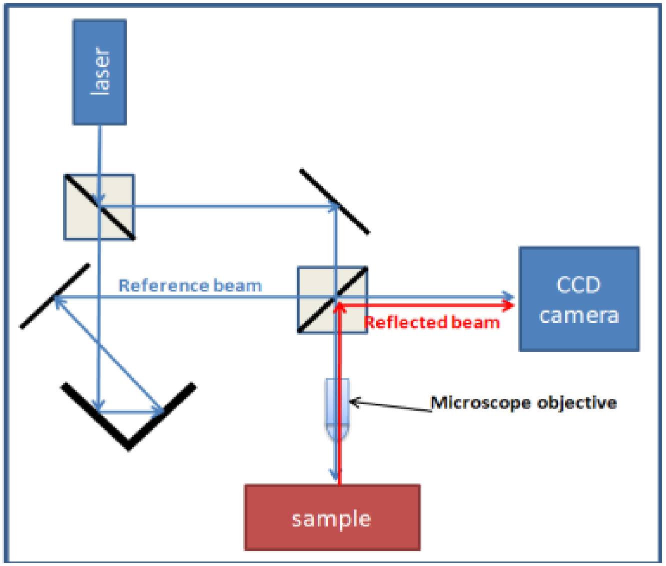
•**<u>Limitations</u>**:

- •Static Images – no dynamic response
- •Resolution changes with magnification
- •Lateral resolution limited by pixel resolution CCD
- •High NA increases resolution, but limits ability to measure sharp steps (walls)
- •Range limited to Z scan stage travel
- •Imaging rate slow for laser scanning (<3 fr./sec)
- •Requires post processing

Digital Holographic Microscopy (DHM)

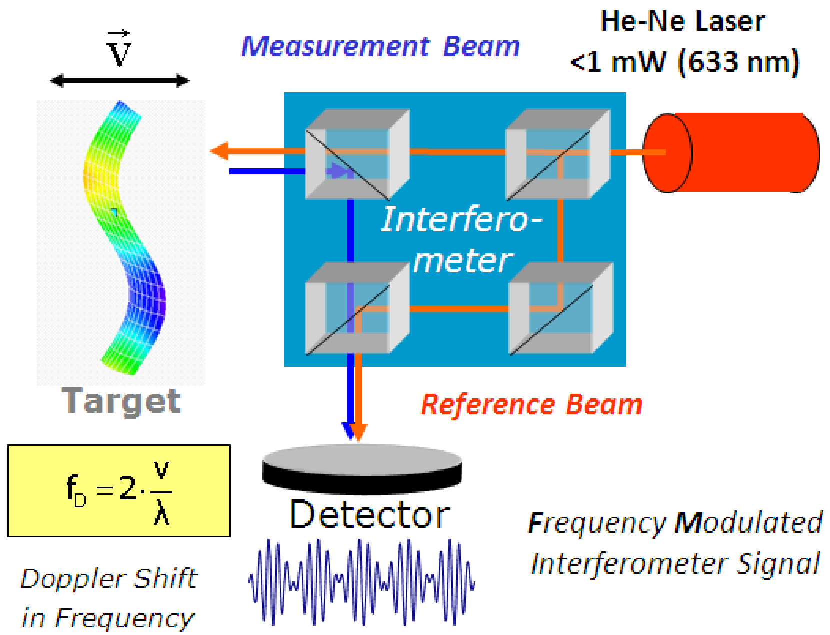
• **3D Imaging** for shape, deformation and vibration measurement
•Similar to interferometry, except wavefronts are numerically reconstructed to form 3D image
•Doesn't require time consuming Z-scan of surface
•Phase aberrations corrected digitally
•Determines shape changes using double exposure, real-time or time-averaging techniques
•Provides measurements of:
    •shape, deformation, stress, vibration
•**Lateral** : < 1 μm
•**Vertical Resolution**: nanometer

•**<u>Limitations</u>**:
    •Best results with rough surfaces
    •A-Priori knowledge object properties to match optical parameters (FL, FOV, NA, pixel resolution)
    •Vertical displacements shift reconstruction distance – may require autofocus
    •Steep angles not possible

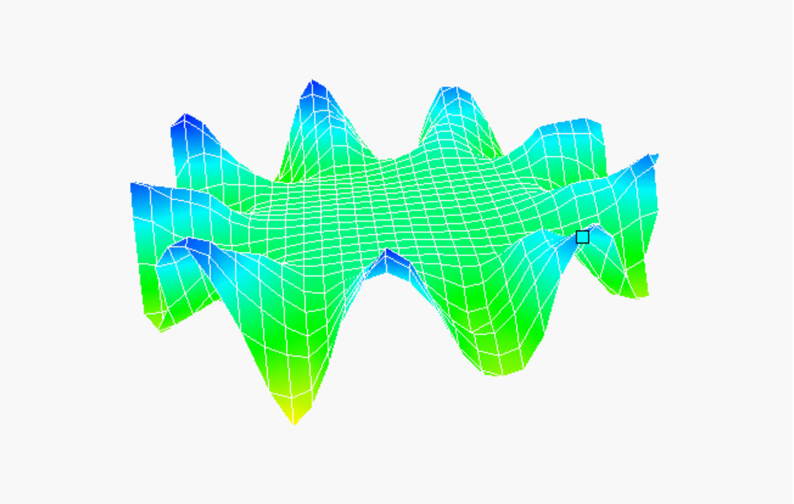


Laser Doppler Vibrometry (LDV)

- **Dynamic Response** (vibration) measurements only
- Fast, accurate, real-time measurement of velocity and/or displacement
- Scanning technique for multi-point measurement and 3D visualization of deflection shapes
- Robust, highly adaptable instrument that measures
  - Resonant frequency
  - Amplitude and Deflection Shapes
  - Settling Time
  - Mechanical properties (damping, elasticity)
- **Lateral Resolution** : 1 um
- **Vertical Dynamic Resolution**: 0.000001 um (**1 pm**)

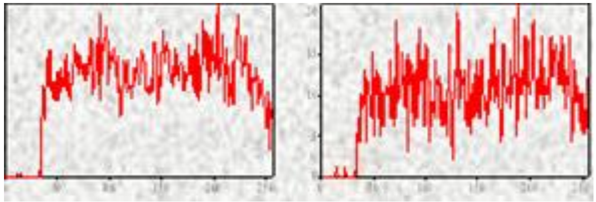


- <u>**Limitations**</u>:
  - Out-of-plane dynamics only
  - Best results on specular (shiny) surfaces
  - Does not measure static shape
  - Does not measure in-plane motion (of MEMS)
  - Single point measurements not full field –scan measurements require point-by-point scan



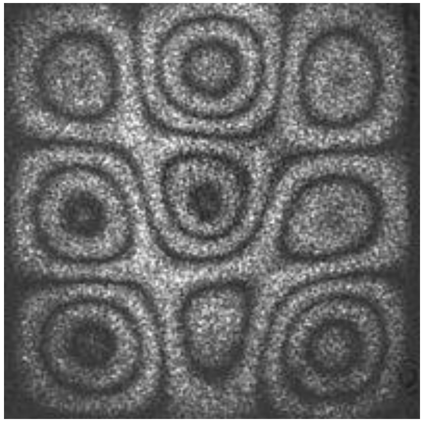
Other Techniques

- **Spectroscopy:**
  - •Chemical composition and crystallinity
  - •Strain



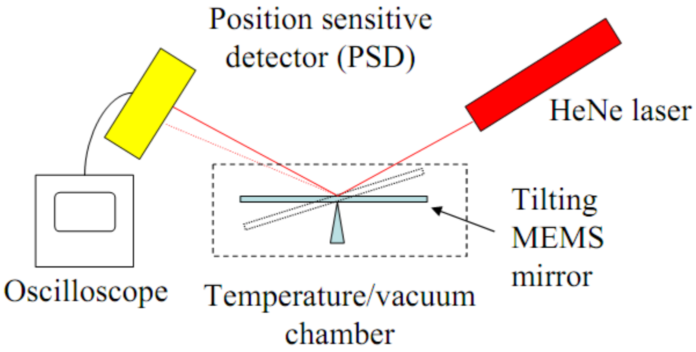
•Ellipsometry:
- •Film thickness and optical parameters

•Electronic Speckle Pattern Interferometry (ESPI)
- •Static and dynamic displacements
- •Requires surface roughness greater than the optical wavelength



•Light Scattering:
- •Micro roughness

•Beam Deflection:
- •Deflection (tilt) response measurements



Comparison MEMS Measurement Instruments

Technique	Lateral Resolution	Vertical Resolution	Static Shape	Dynamic Response	Starting Price
AFM (Atomic Force Microscopy)	0.0001 μm	0.0001 μm	3D	No	$$
SEM (Scanning Electron Microscope)	0.001 μm	N.A.	2D	No*	$$$$
OM (Optical Microscopy)	<1 μm	<1 μm	2D	No*	$
WLI (White Light Interometer)	<1 μm	<0.001 μm	3D	No**	$$$
CM (Confocal Microscopy)	<1 μm	0.01 μm	3D	No	$$
DHM (Digital Holographic Microscopy)	<1 μm	0.001 μm	3D	Yes	$$$
SVM (Strobe Video Microscopy)	0.01 μm***	<1 μm	No	Yes	$$$
LDV (Laser Doppler Vibrometry)	<1 μm	10^{-6} μm***	No	Yes	$$

$	*Inexpensive - below $10,000*
$$	*Some Expense –$10,000 to $50,000*
$$$	*Moderate Expense –$50,000 to $150,000*
$$$$	*Expensive – over $150,000*

* *Dynamic response possible using video capture technique*

** *Dynamic response possible using strobe technique*

*** *Resolution for dynamic response – not static*

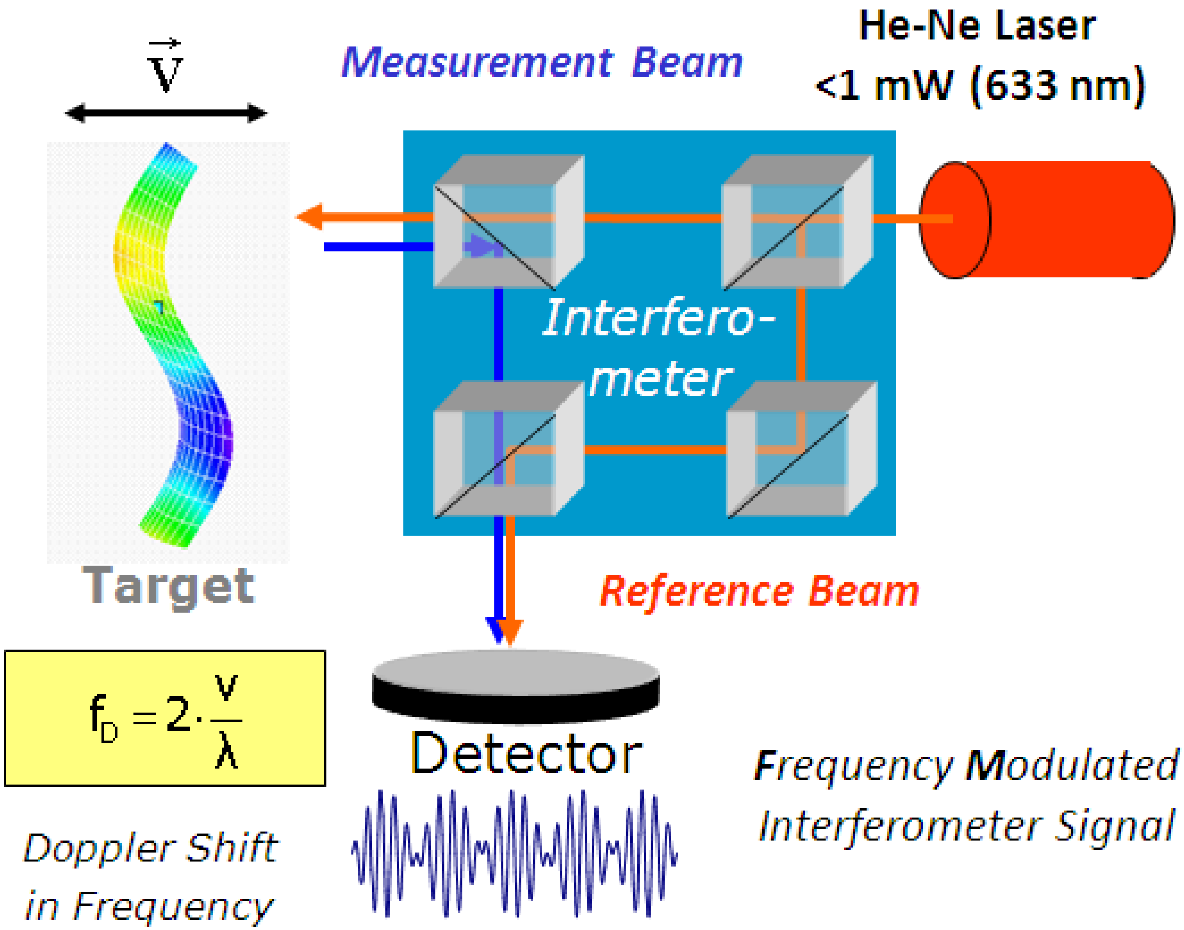
Why Dynamic Response Measurements?

→MEMS usually involve active **moving elements** for sensing and actuation

Examples:

μmirrors: settling time response
Resonators: amplitude response
Cantilevers: modulus elasticity

Laser Vibrometry provides a unique solution for highly sensitive, real-time measurements of out-of-plane vibration.



$$f_D = 2 \cdot \frac{v}{\lambda}$$

Micro System Analyzer (MSA-500)

Polytec

Polytec Micro System Analyzer:

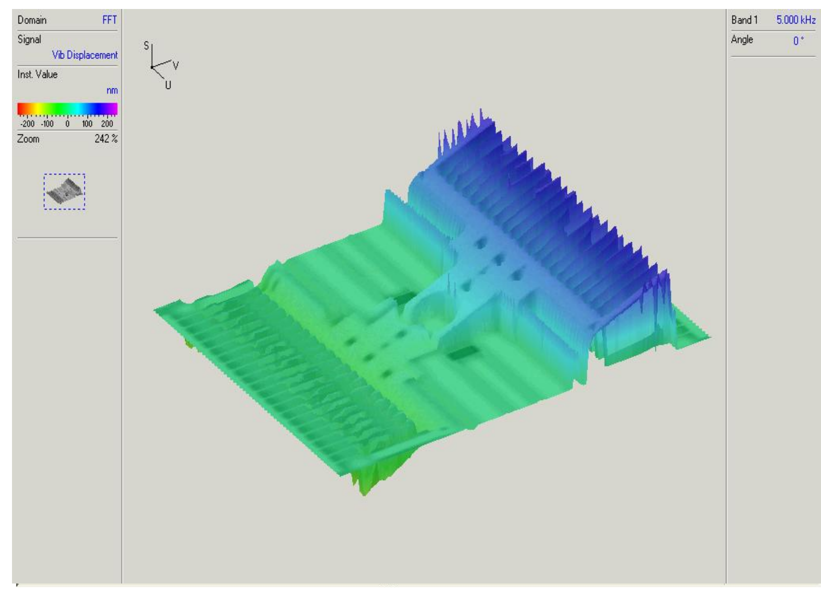
Combines techniques for precise 3D analysis of structural vibration and surface topography:

(LDV + SVM + WLI)

•**Scanning Laser Vibrometry** for fast measurement and 3D visualization of out-of-plane deflection shapes.

•**Strobe Video Microscopy** for capturing and analyzing in-plane motion.

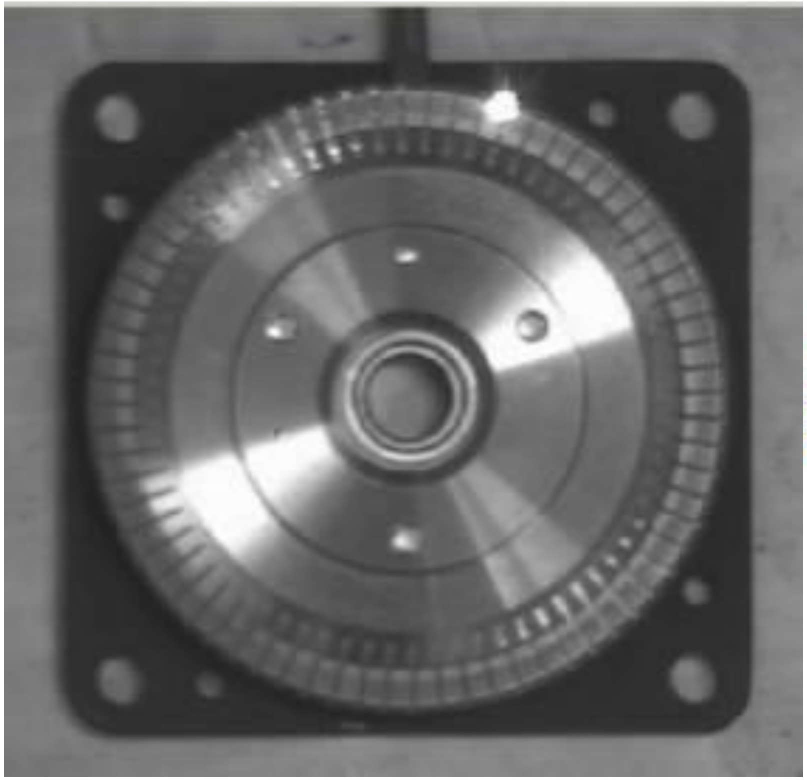
•**White Light Interferometry** for mapping surface topography.



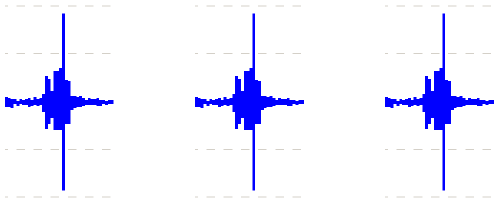
Technique Scanning Laser Vibrometry

Polytec

piezo motor

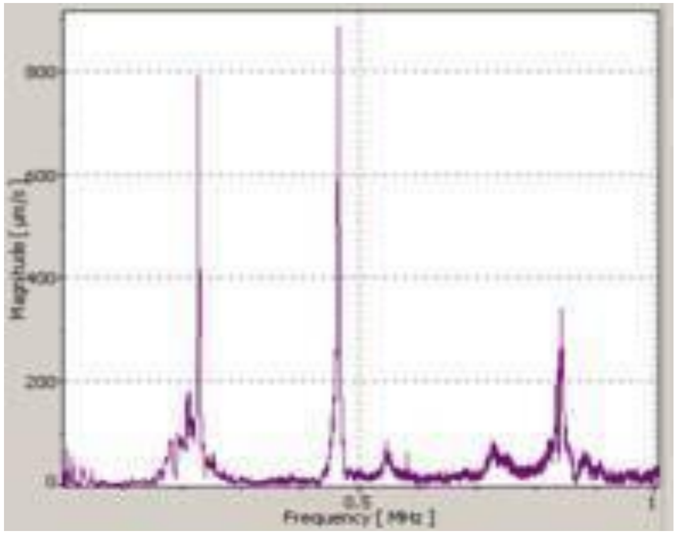


Vibration Time Signal



sequential measurement at all points. Excitation for all points

Vibration Spectrum



Laser Doppler Vibrometry

Polytec

Advantages:

- **Real Time Measurement**: Fast, signal-based measurements from broadband excitation; can measure transient response
- **High Resolution:** Displacement resolution down to *picometer*
- **High lateral resolution:** Laser spot focused down to 700 nm
- **High frequency bandwidth**: DC to 24 MHz (1.2 GHz)
- **High accuracy:** Doppler technique highly accurate and linear
- **Can do difficult measurements** on range of materials, under required environmental conditions, i.e. thru glass into a vacuum chamber → calibration independent of these factors
- **Probe Station Integration:** Integrates with commercially available probe stations for wafer level testing

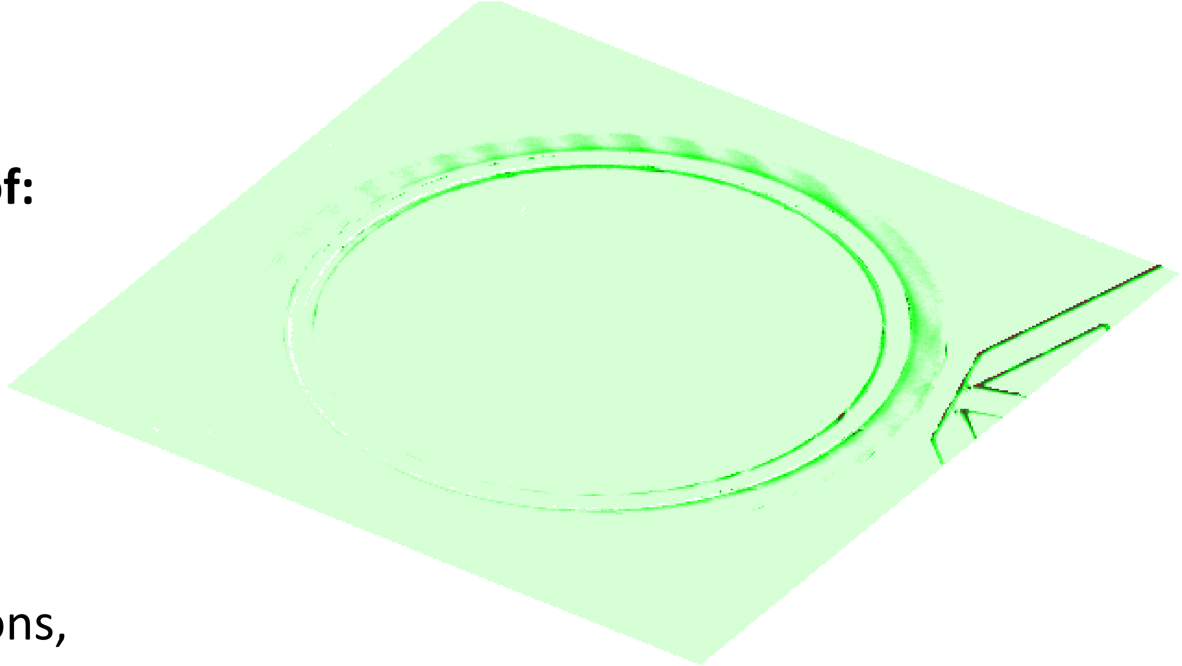
Limitations:

- **Scan Measurement not full field**: scan measurements are taken sequentially point-by-point across the field of view
- **Dynamic response only:** no static shape measurements; object needs to move
- **In-plane movement not measured:** in-plane measurement technique does not work on MEMS due to specular surfaces; must use alternate techniques such as strobe video microscopy
- **3D data set not combined:** in-plane and out-of-plane measurements taken seperately
- **Lateral Resolution limited by optics:** diffraction limit 632 nm; difficult to scale down to nano scale (i.e. NEMS or carbon nanotubes)
- **Three Wave Mixing:** light reflected from multiple surfaces (i.e. transparent layer) can interfere causing three wave mixing and effect accuracy of measured amplitudes

Topography: White Light Interferometry

Additional Topography Measurement Capability

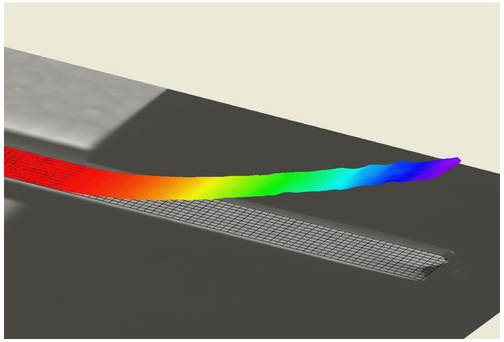
Using Integrated White Light Interferometry

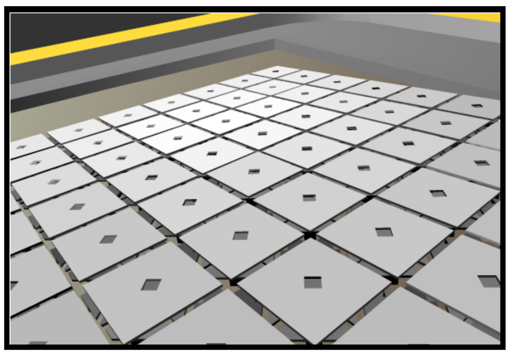


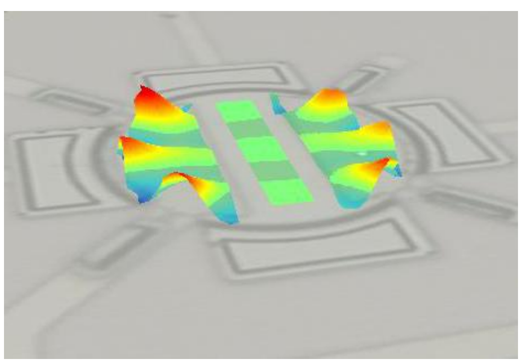
Topographical Measurement of:

- Step-Height
- Shape (Curvature, Flatness)
- Roughness
- Form Parameters (Dimensions, Angle, Radius)

Measurement Examples on MEMS







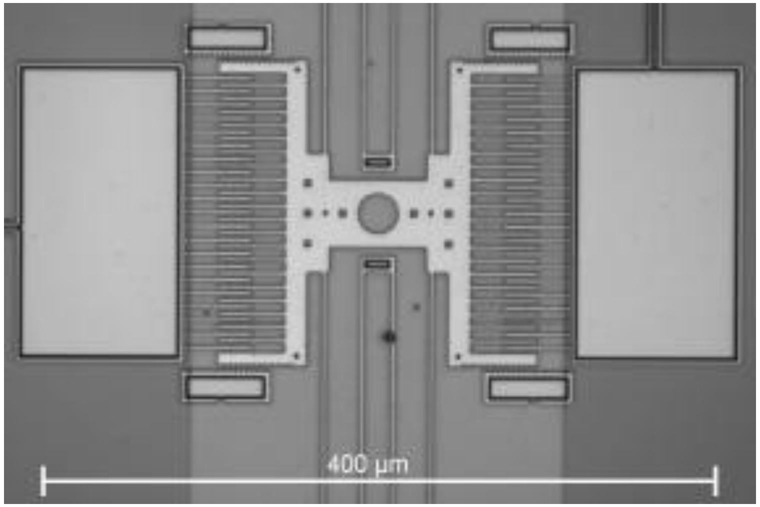
1. Sandia Comb Drive Actuator
2. Texas Instruments μmirror array
3. Sandia & AFM Cantilever
4. XComm Wireless RF Switch
5. UCI Inertial Sensor
6. UCB Resonator

1. MEMS Comb Drive Actuator

In-plane actuator driven by electrostatic pulling force

$$F = \frac{1}{2}\varepsilon\frac{nh}{g}V^2$$

Restoring force from bi-fold springs



Resonant Frequency given by:

$$\omega_0 = \sqrt{\frac{K_{eff}}{M_{eff}}}$$

Substituting for K_{eff} and M_{eff}:

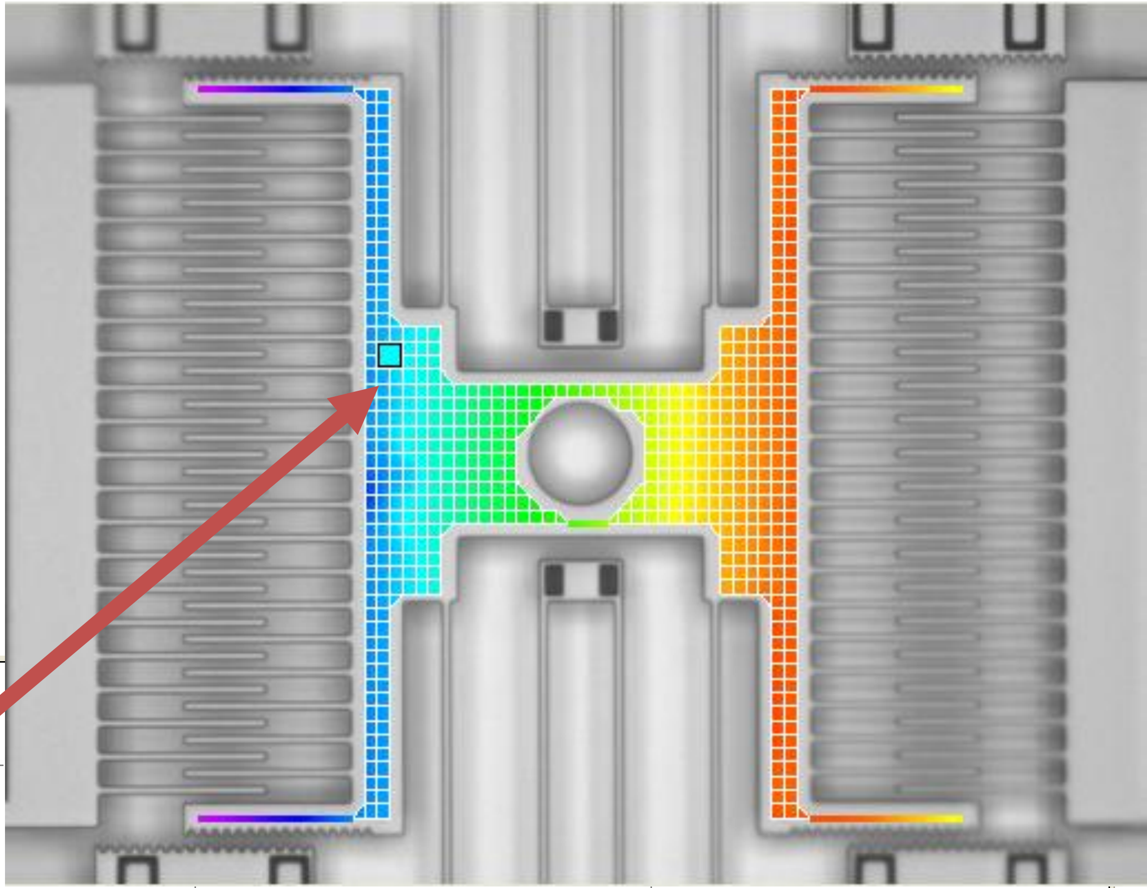
$$\omega_d = \sqrt{\frac{E\,w^3(1-\zeta^2)}{\rho L^3 A_{eff}}}$$

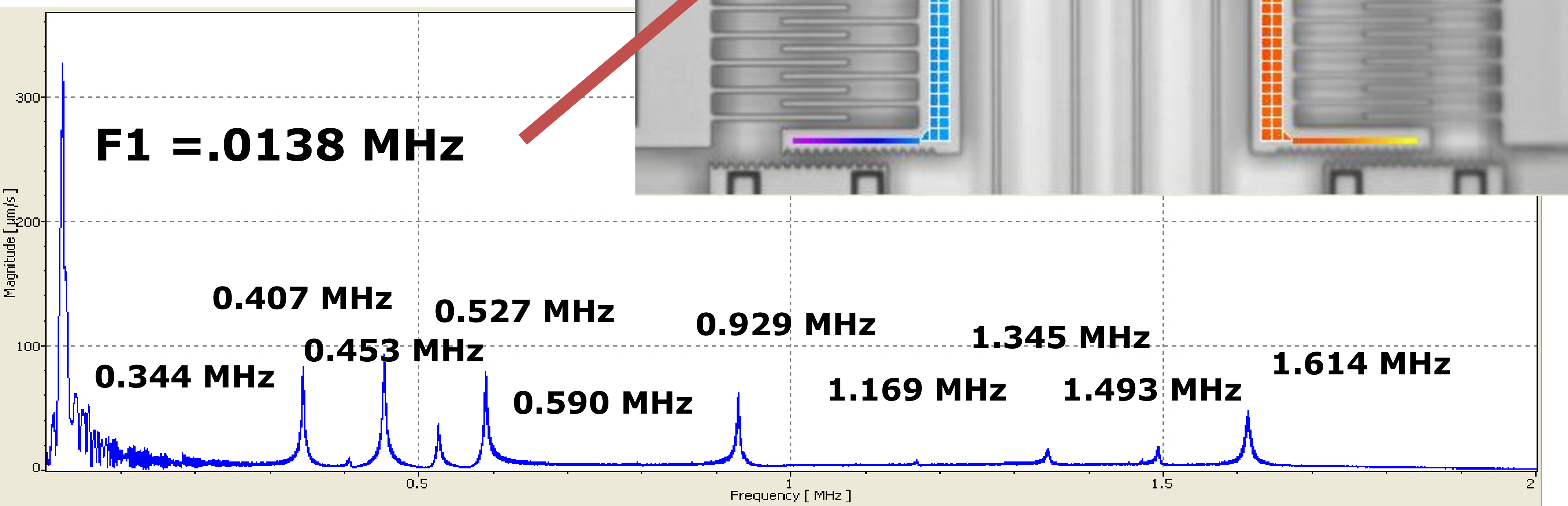
Where E is Young's Modulus of Elasticity, w is spring width, ρ is the density, L is the spring length and A_{eff} is the effective area of comb drive.

1. MEMS Comb Drive Actuator

Frequency Response

- Set up a grid of approximately 700 measurement points
- 80 Volt Burst Chirp Excitation to 2 MHz, 25600 Lines FFT
- **Measurement time each spot 12.8 ms** (chirp response)
- Frequency Response Function measured for each point
- Automatically Scan measurement for all points

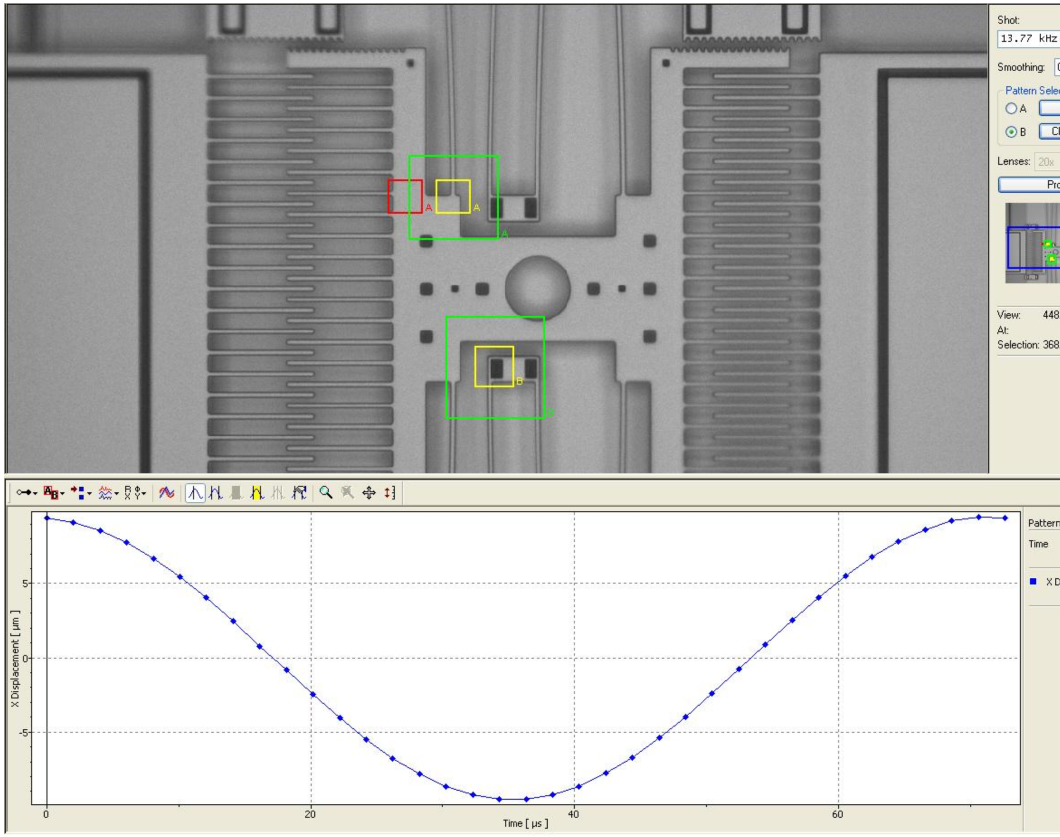




1. MEMS Comb Drive Actuator

In-plane motion measured by Strobe Video Microscopy

- Imaging system that acquires strobe image sets at specified frequencies and phase angles
- Pattern matching to determine displacements
- Software tools for analyzing response



Specifications:

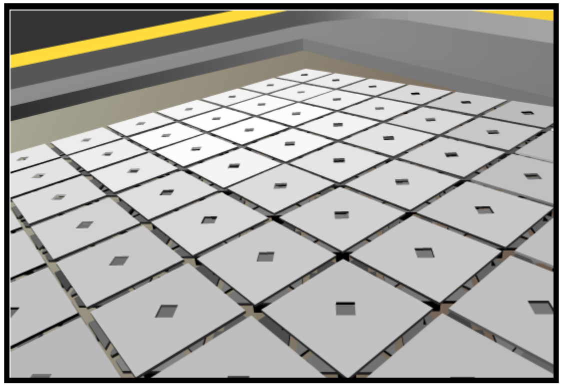
- High image resolution progressive scan camera (1.3MPixel).
- Displacement resolution at .005 pixel
- High power LED with short 100ns flash pulse and incoherent light.

2. μmirror array

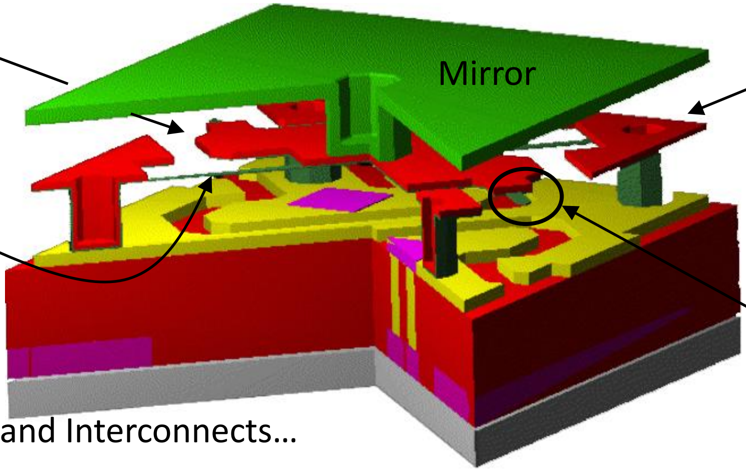
Courtesy Dr. Rick Oden, Texas Instruments

DLP™
A TEXAS INSTRUMENTS TECHNOLOGY

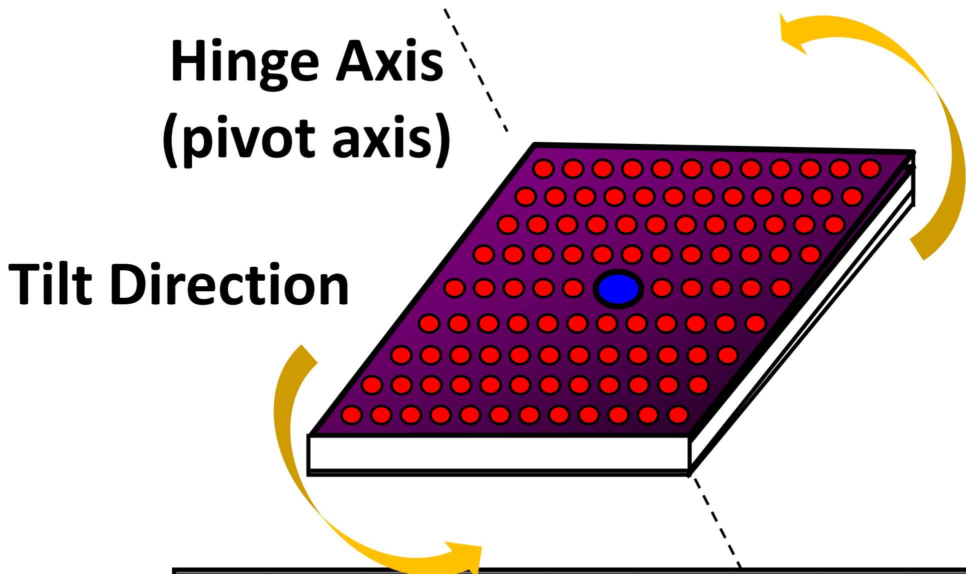
- **Settling time dynamics** of whole mirror array (3D image of time sequence)→scanning vibrometry
- 12.7μm mirrors in massive array
- Tilts of the pixels are ±10 or ±12 degrees…



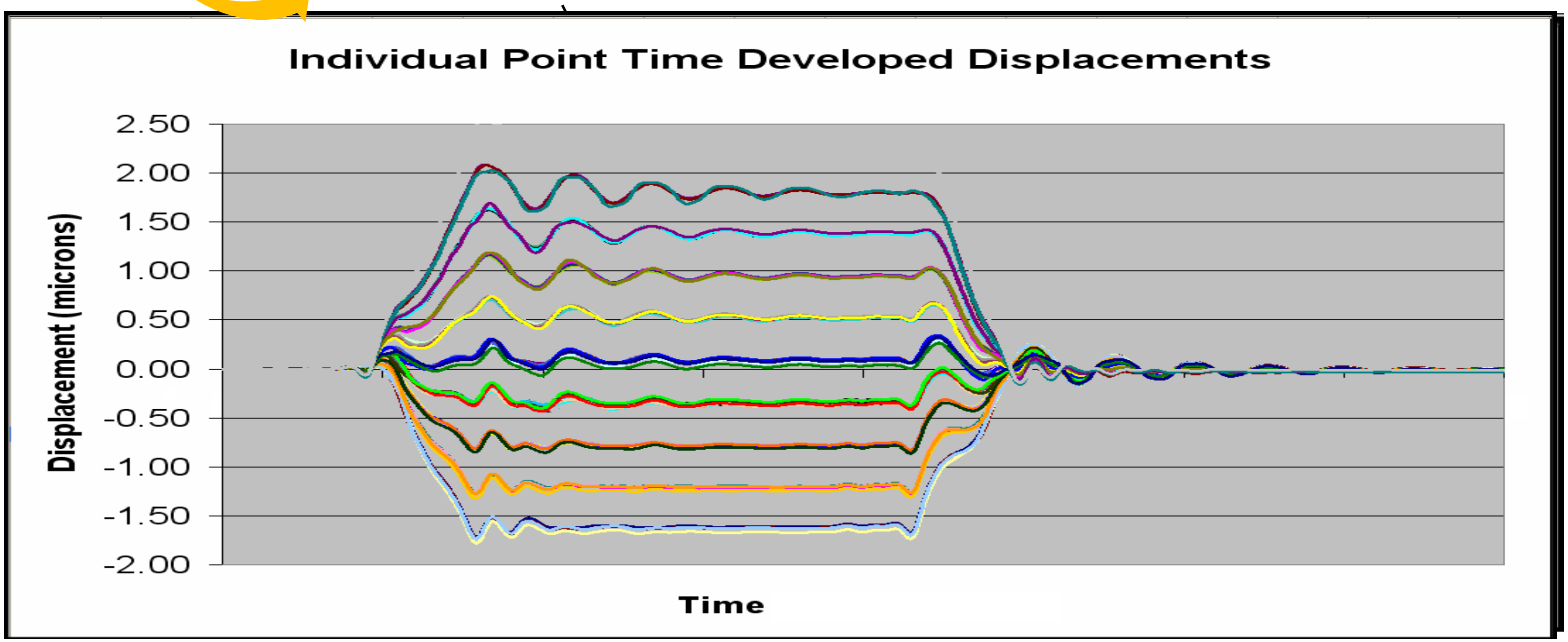
"Because the heart of the projector system is the DMD mirror array – a thorough understanding of the dynamic motion of the mirrors is critical to gauge performance of current as well as future technology directions…"



2. μmirror array



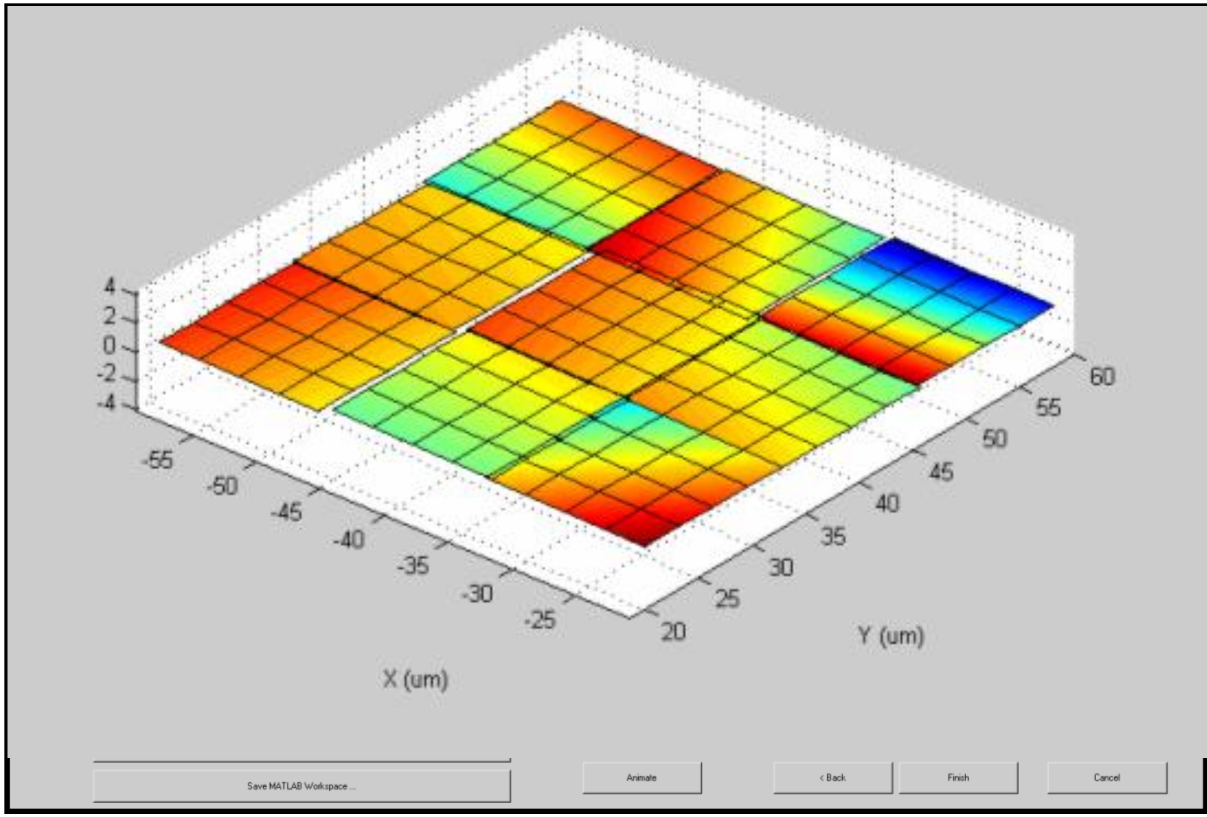
- As mirror transitions from “off” to “on” state (‘-’ to ‘+’ for example), the MSA system can acquire a time domain response of this point on the mirror…



2. μmirror array

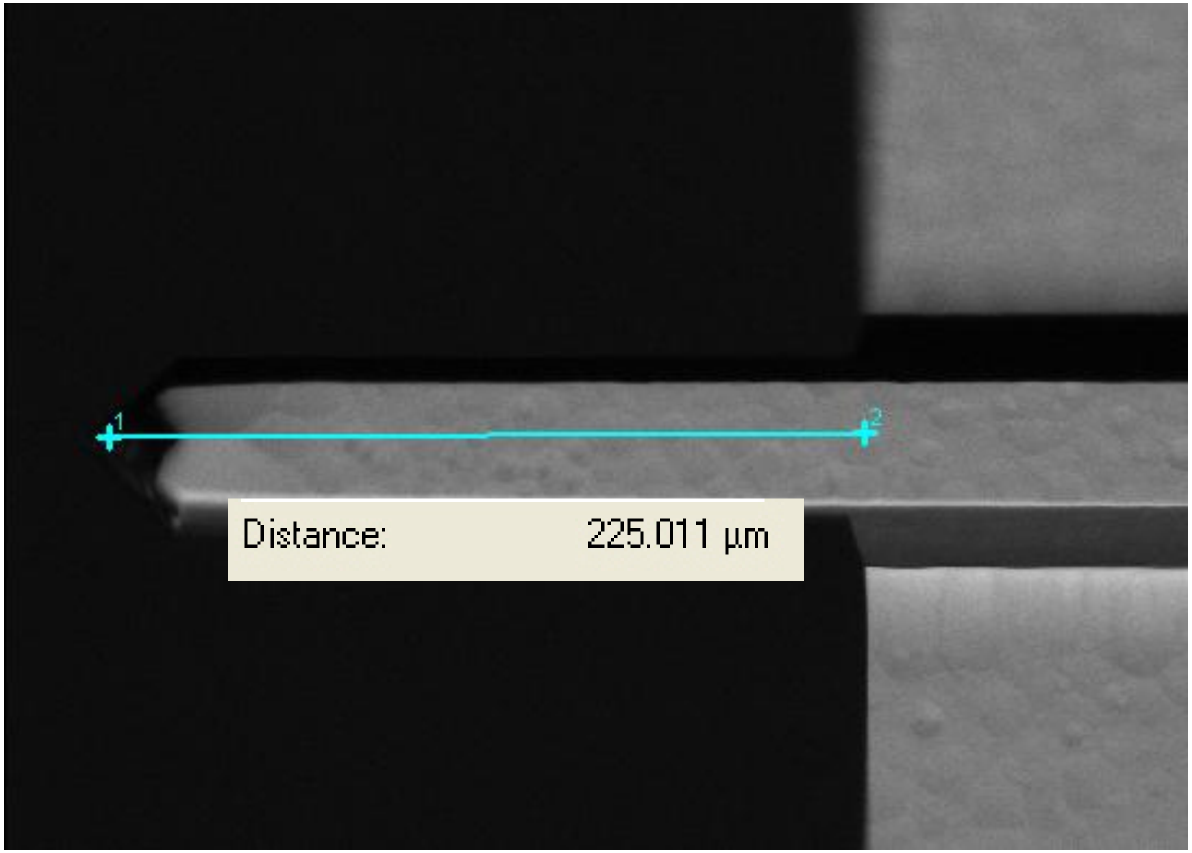
3D Visualization

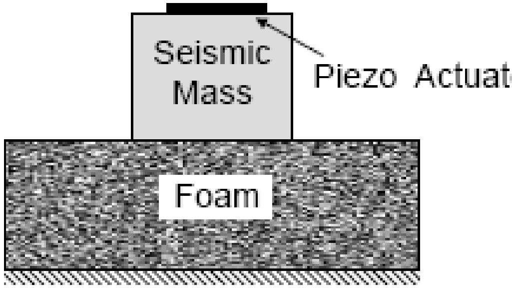
• Image shows 3D animation of settling time response mapped across array

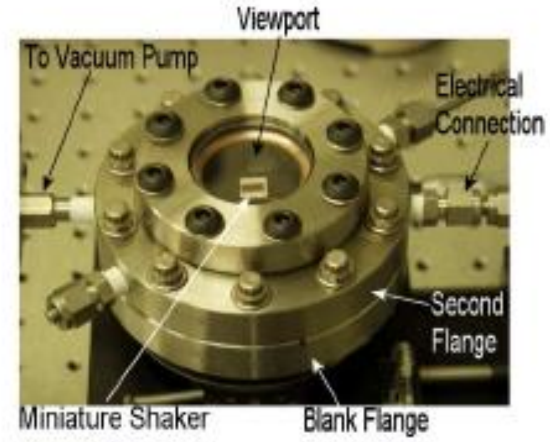


• In this case, a (3x3) array of mirrors are shown with their corresponding tilt, roll and sag axis time developed.

3. Cantilever







- Methodology is used for determining **Young's modulus of elasticity** and damping

$$f_i(Hz) = \frac{\lambda_i^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}}$$

<u>Natural Frequency</u>

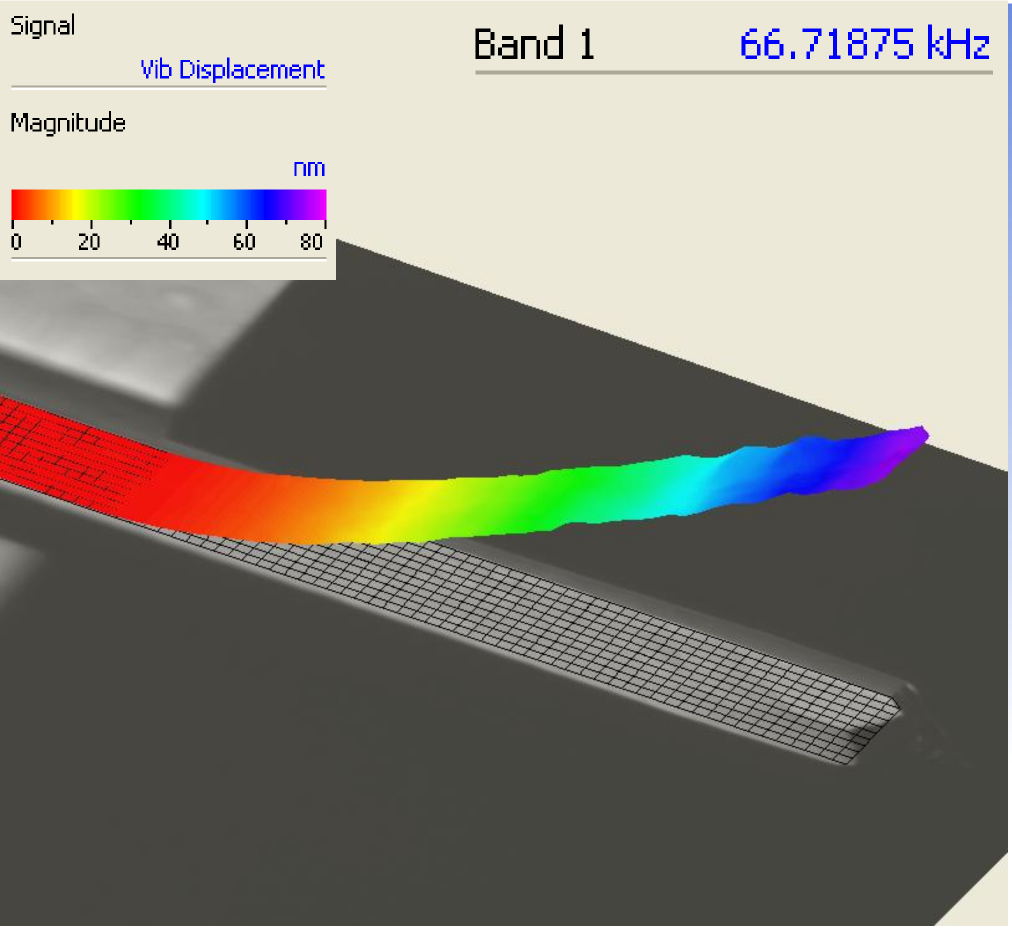
3. Cantilever

Comparison with FEA Model

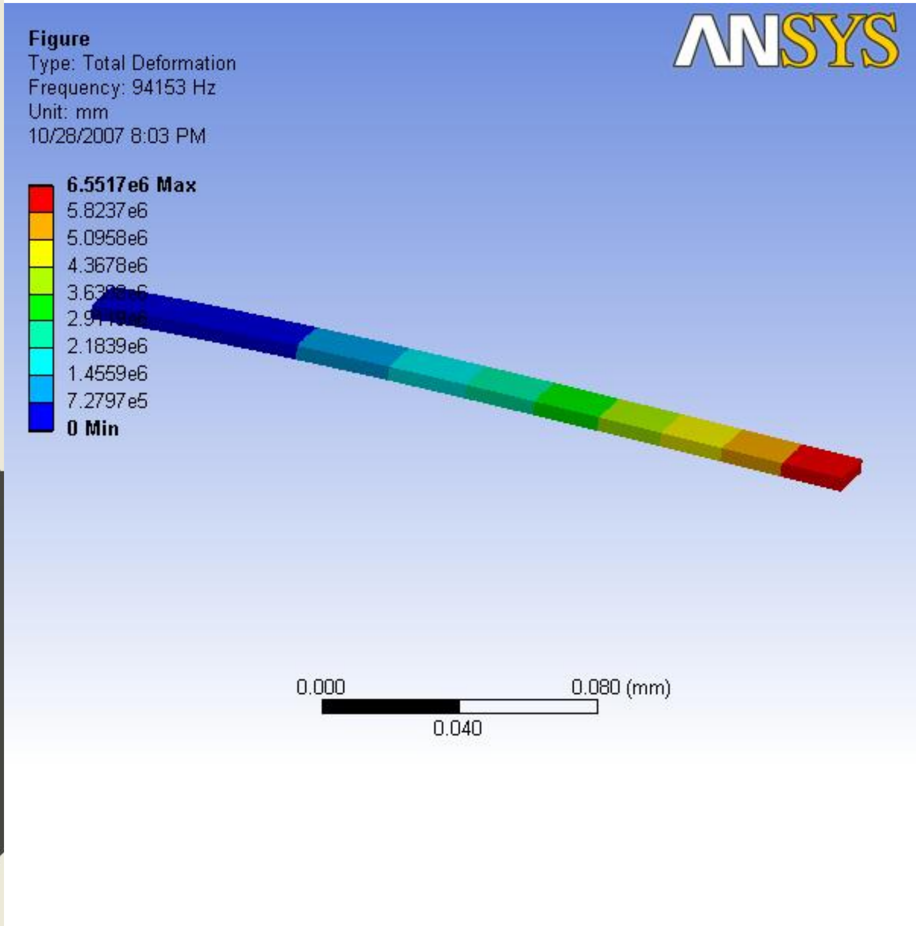
1st Bending Mode

Discrepancy: -29%

Experimental Data:



Model:



3. Cantilever

Sandia National Laboratories

Topography measurement

•Cantilever Array with lengths ranging from 100 to 1800 μm

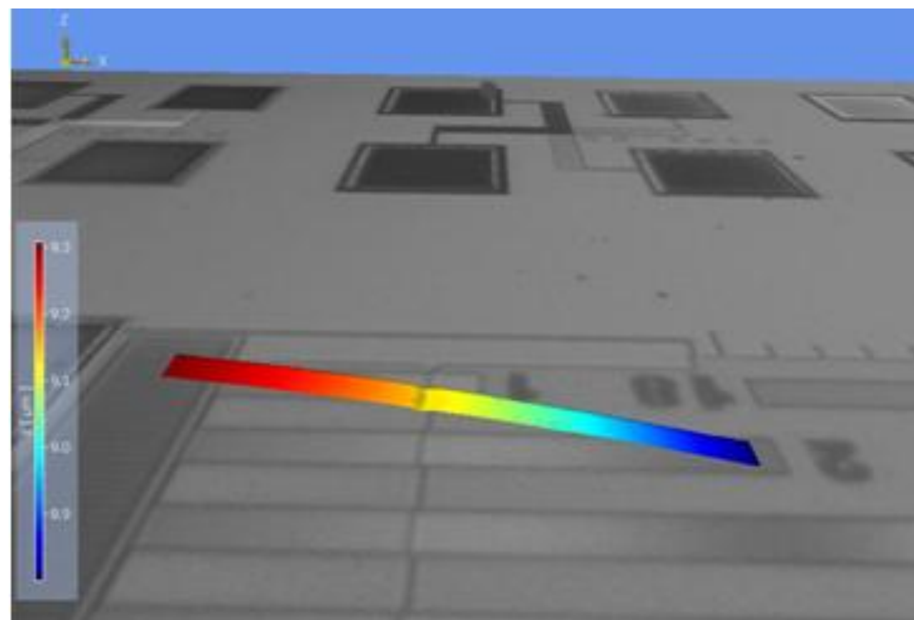
•Stress gradient causes “curling” along length of structure

•Measurement taken on 200 μm beam

•Downward curl is mapped in 3D

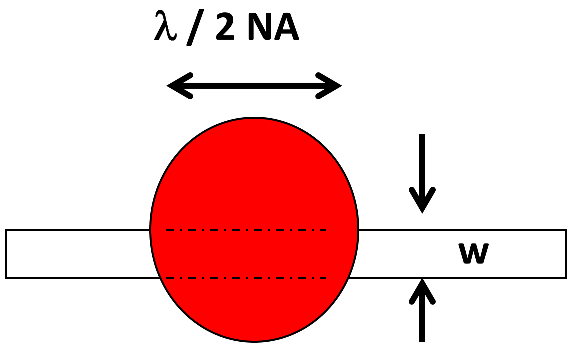
•Profile measurement with polynomial line fit

•Tip curls downward 502 nm at tip

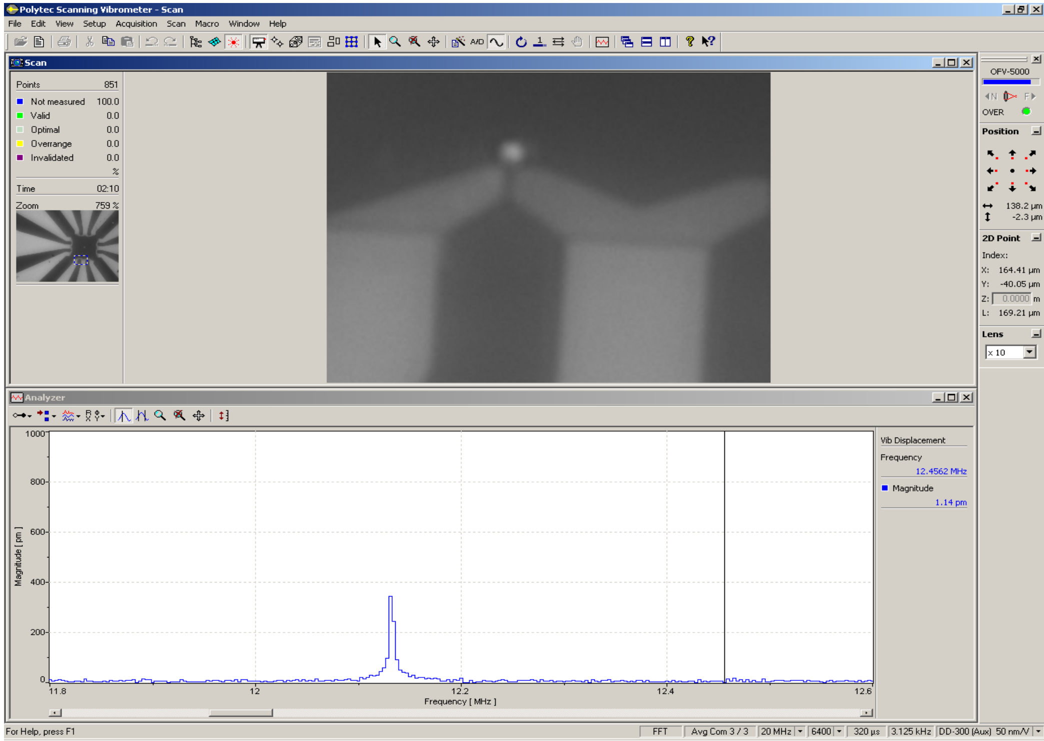


3. Cantilever

Nano Electro-Mechanical Structures (NEMS)



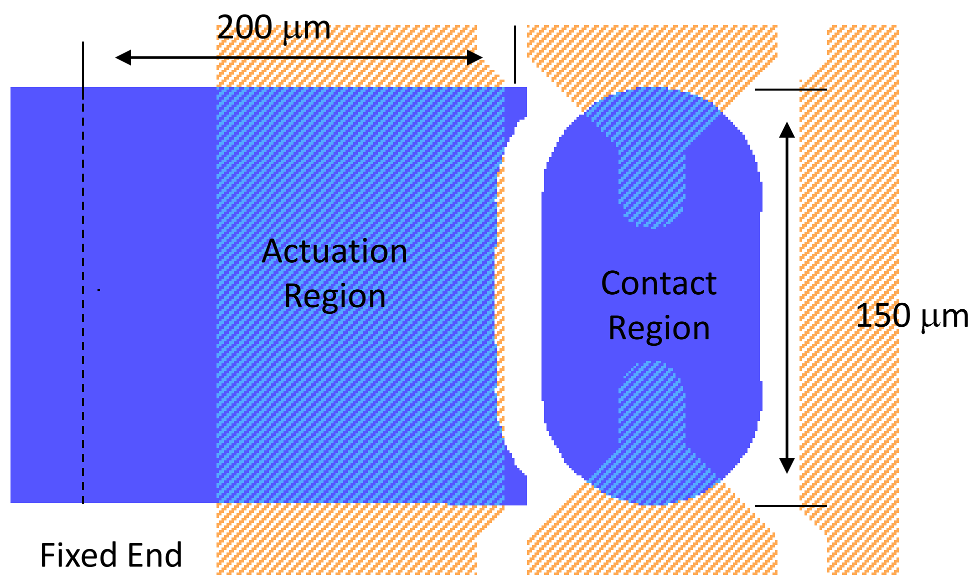
- Measurement on NEMS cantilever with length 2 um and elements several 100 nanometers wide.
- “Invisible” to CCD camera
- In vacuum at 200 milliTorr.
- External excitation by piezo.



4. RF Switch

Floating Cantilever Design

Xcom Wireless RF Switch



- Dimension : 200 x 150 μm
- Switch gap at contact region g_0 = 2 μm

- Snap down occurs when actuation region is pulled down g_0 / 3

Snap down voltage:

$$Vp \cong \sqrt{\frac{8kg_o^3}{27\,\epsilon\,A}}$$

where *k is spring constant*

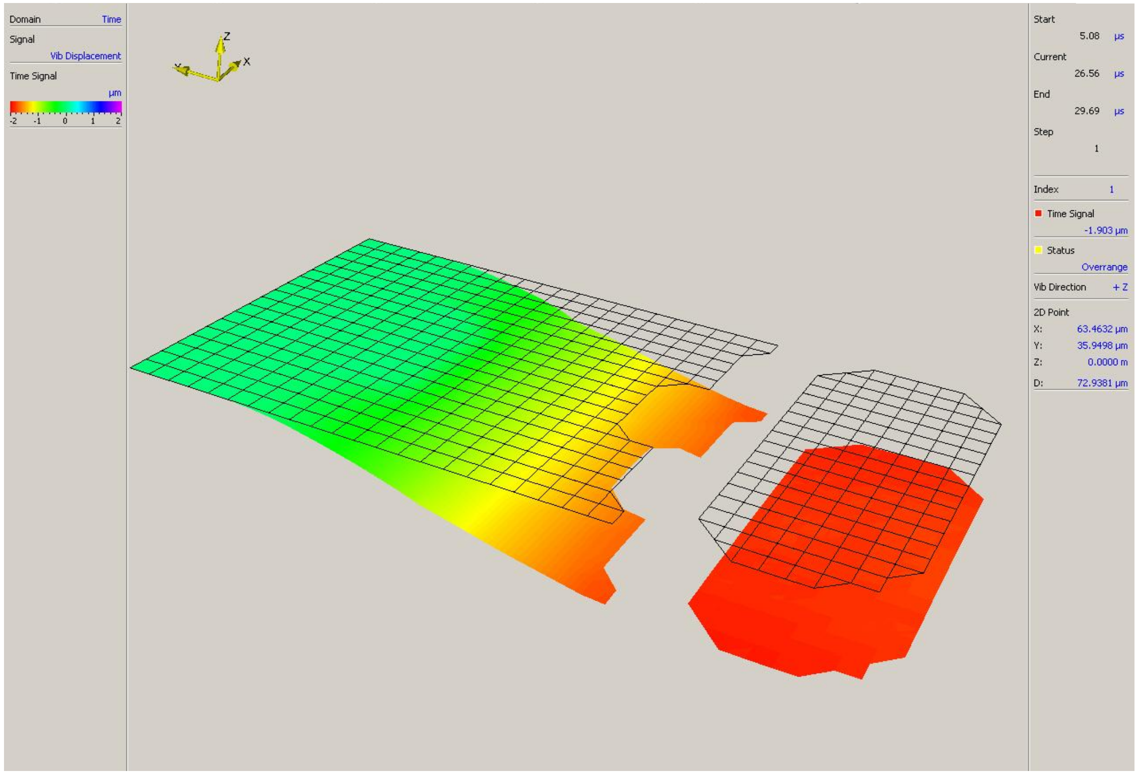
A is area of actuation region

ε is dielectric constant

4. RF Switch

Snap down response of RF MEMS Switch showing deflection shape

Displacement time history at select point on structure



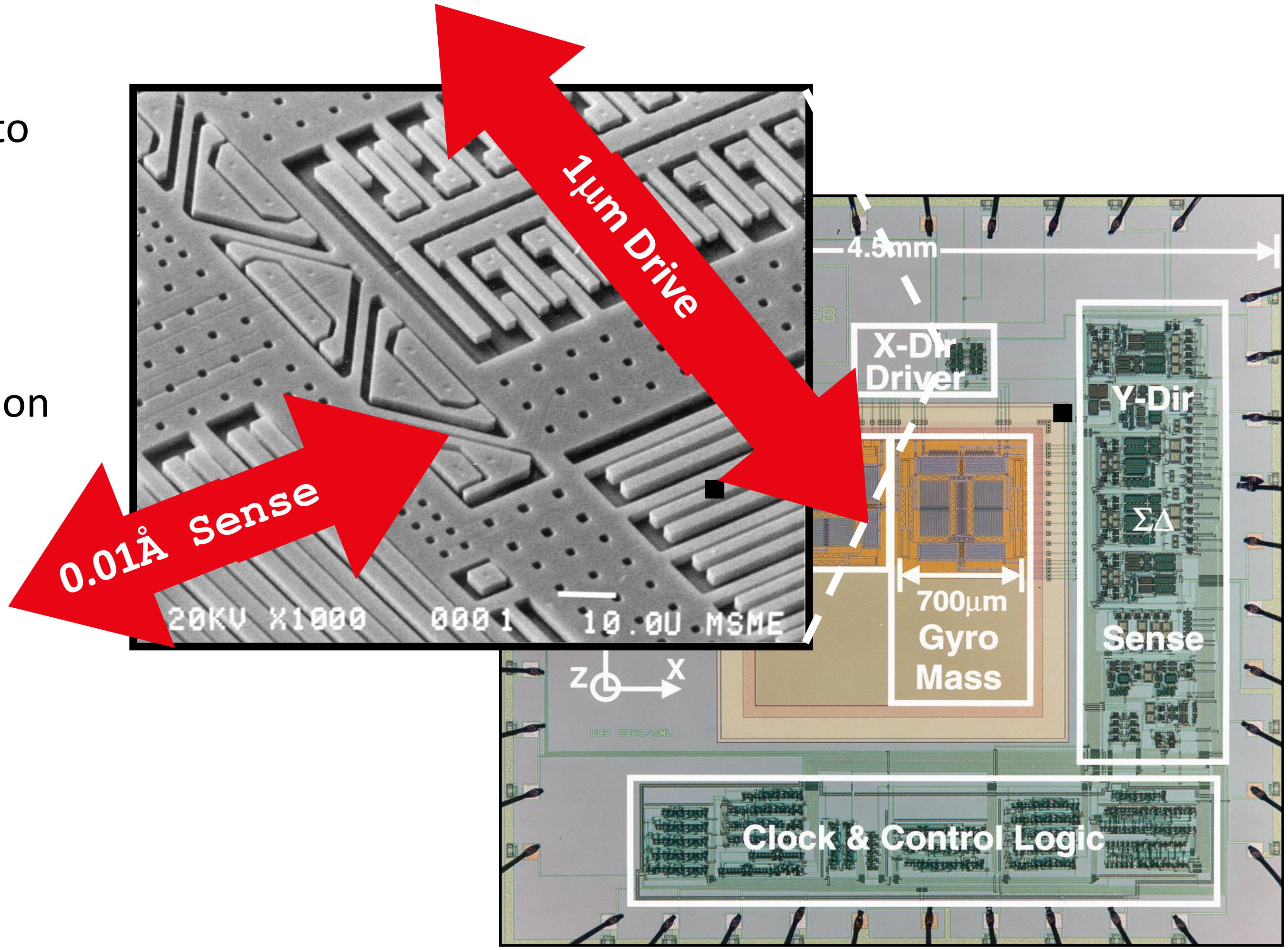
•Settling time measurements to determine the switching speed and resonant frequency of the device

5. Inertial Sensor

•**3D Motion Analysis** to characterize complex response and identify defects

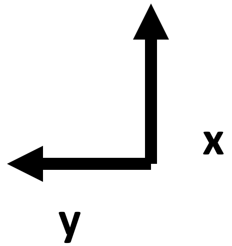
•Experimental validation of device response to compare with FEM model

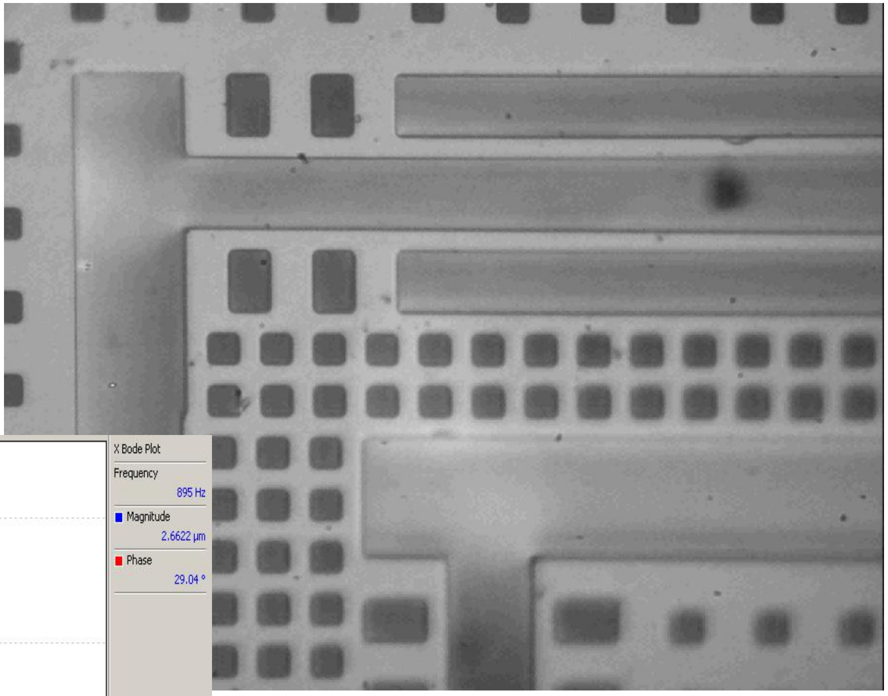
•Troubleshooting spurious modes of vibration effecting performance

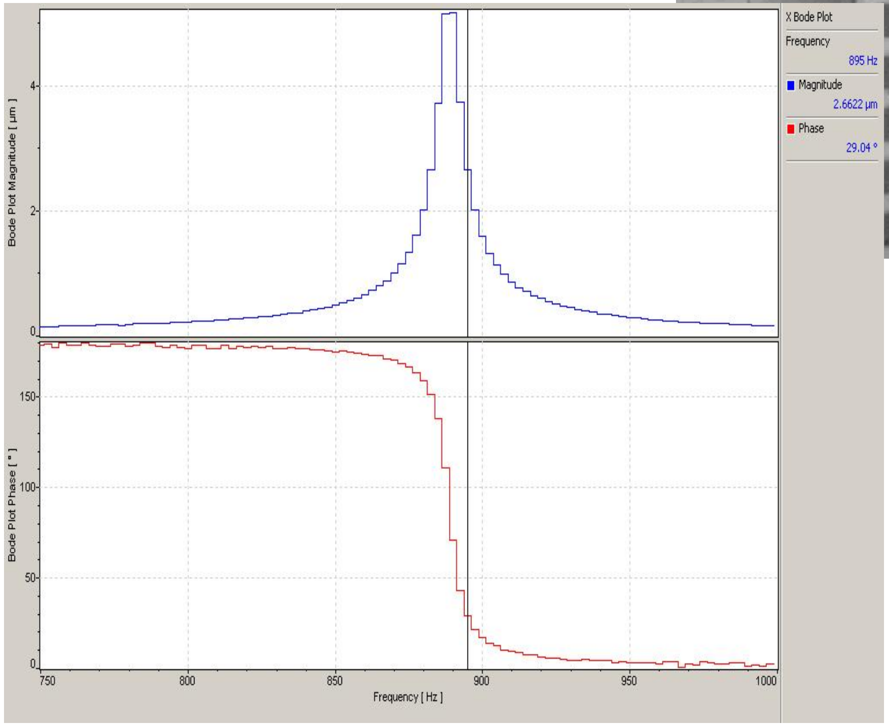


5. Inertial Sensor

Drive Mode Response
at 895 Hz





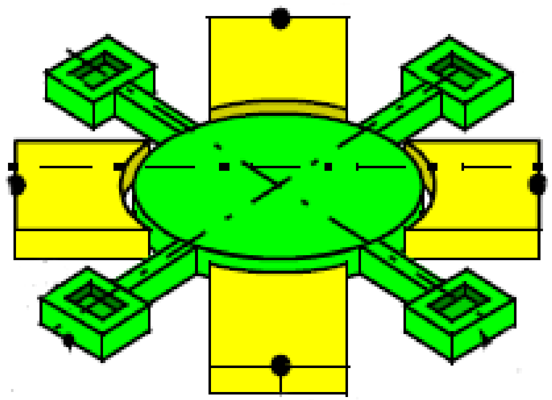


Courtesy Dr. Cenk Acar, UCI

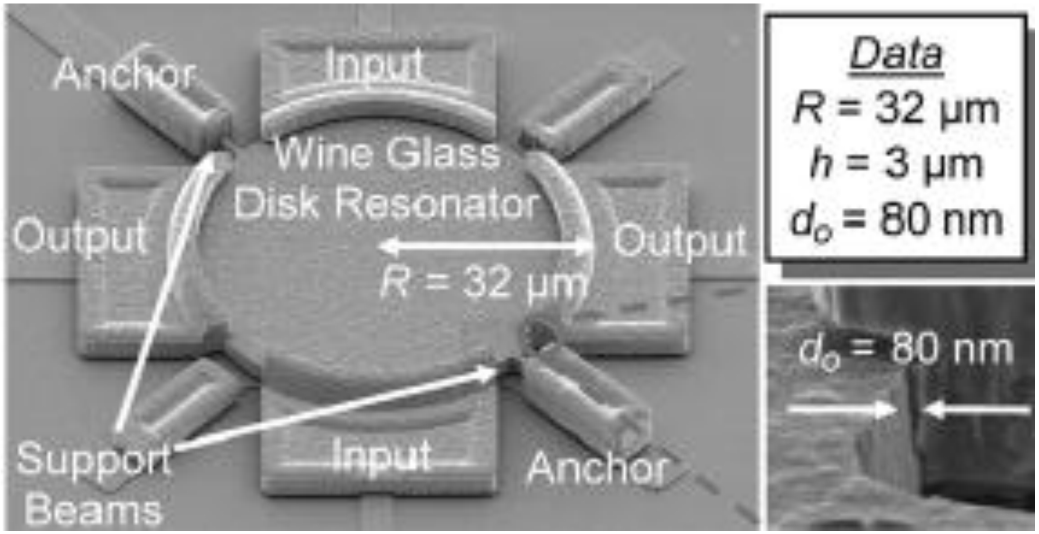
Sense Mode Response
at 1500 Hz

6. Resonator

Courtesy Dr. Clark Nguyen, BSAC

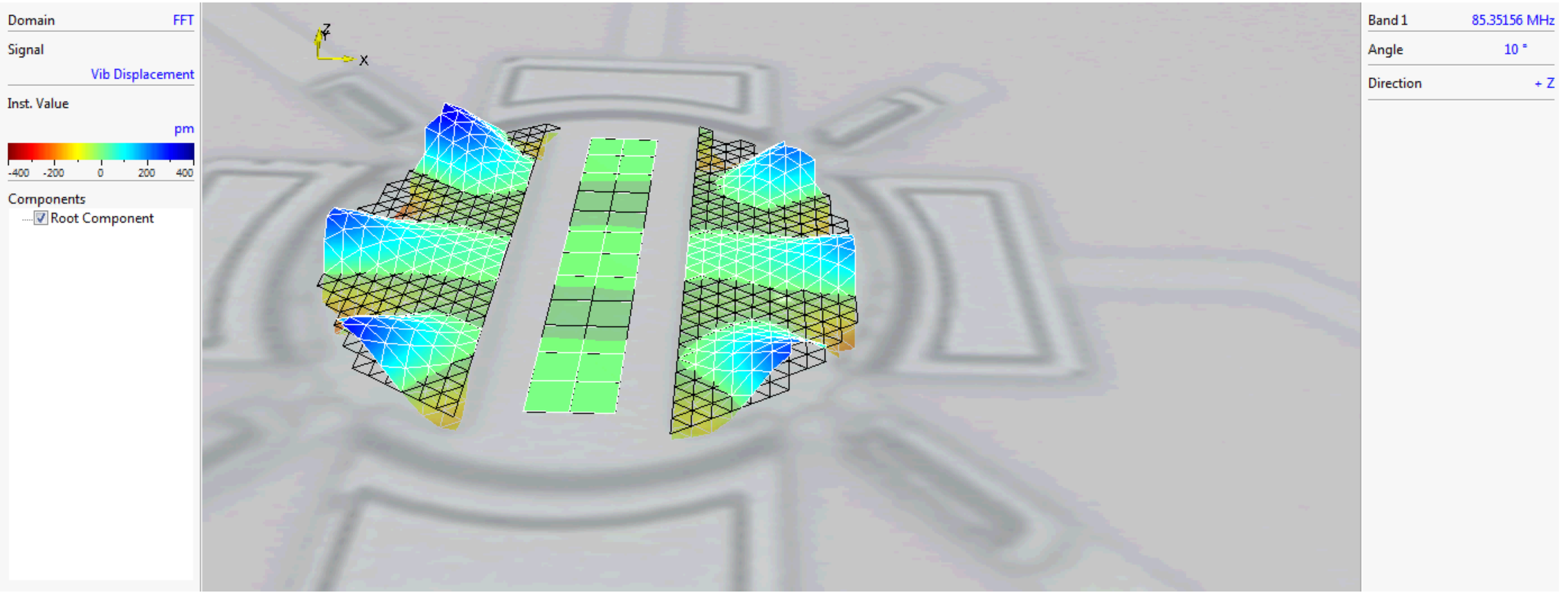


- Vibrating MEMS Resonator
- On-chip high-*Q resonators designed for use in wireless communication systems* for frequency generation and filtering.



- Disk resonator with frequency 61.2 MHz
- High Q factor (>10,000 in air)
- Four electrodes surround the disk with a lateral electrode-to-disk gap spacing of only 80 nm

6. Resonator



Scan measurement of higher frequency mode at 85.35 MHz

Conclusion

- Diverse Range of tools available for MEMS characterization - each with their own advantages
- Polytec MSA unique, all-in-one optical measurement solution for 3D vibration measurement plus topography measurement
- Real-time, broadband measurement with frequency response in milliseconds
- Highly Sensitive measurement with resolution down to picometer level
- Well supported by engineers knowledgeable with MEMS applications and necessary requirements for testing