Micromachined Accelerometers

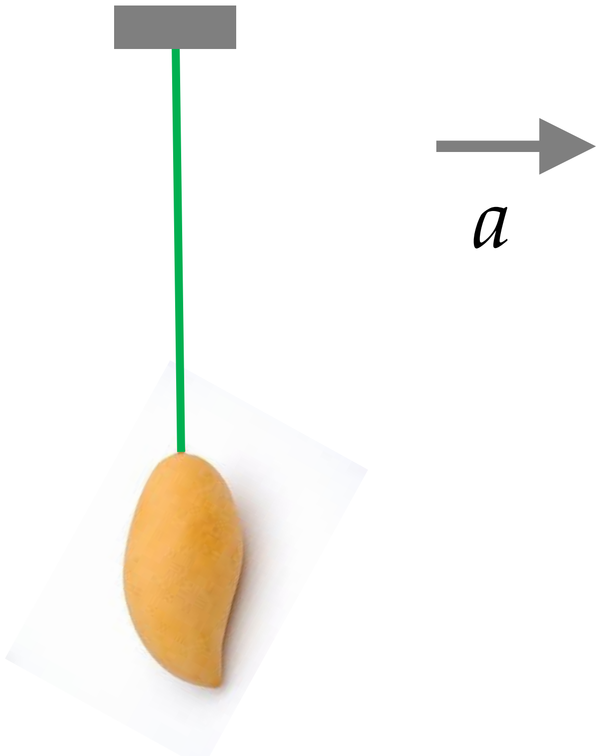
G.K. Ananthasuresh
suresh@iisc.ac.in

Work done with Dr. Sambuddha Khan

Funded by NPOL -Kochi (Dr. V. Natarajan)

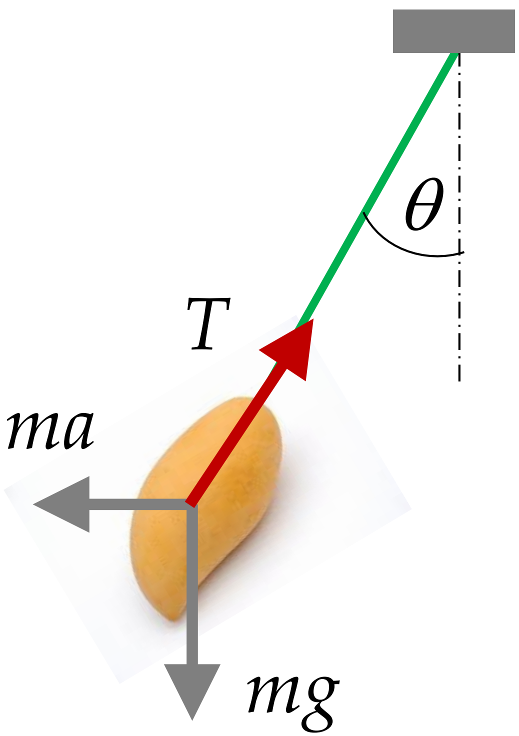
What’s an accelerometer?

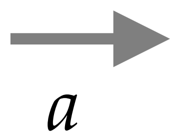
How will you measure acceleration if you are traveling in a train?



What's an accelerometer?

How will you measure acceleration if you are traveling in a train?

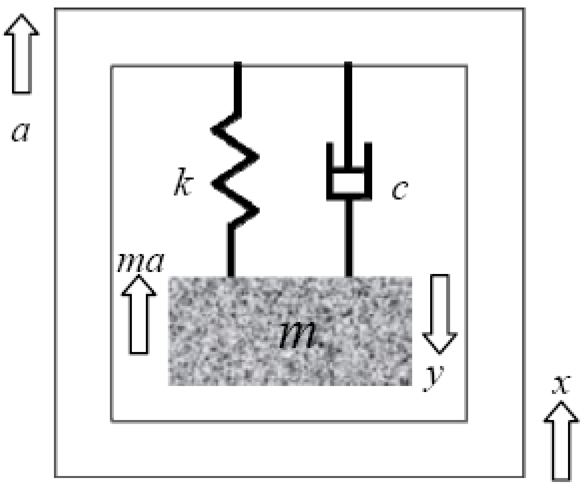




$$\tan\theta = \frac{ma}{mg} \Rightarrow a = g\tan\theta$$

Working principle of an accelerometer

- All you need is a mass, a spring, and a damping mechanism.
- Some means of measuring displacement of the mass.



$$m\ddot{z} + c\dot{z} + kz = ma$$

where, $z = y - x$

At steady state…

$$kz = ma \Rightarrow \frac{z}{a} = \frac{m}{k}$$ **Sensitivity**

$$\omega_n = \sqrt{\frac{k}{m}}$$ **Resonance frequency**

High sensitivity implies low resonance frequency;

Low resonance frequency implies small operational range.

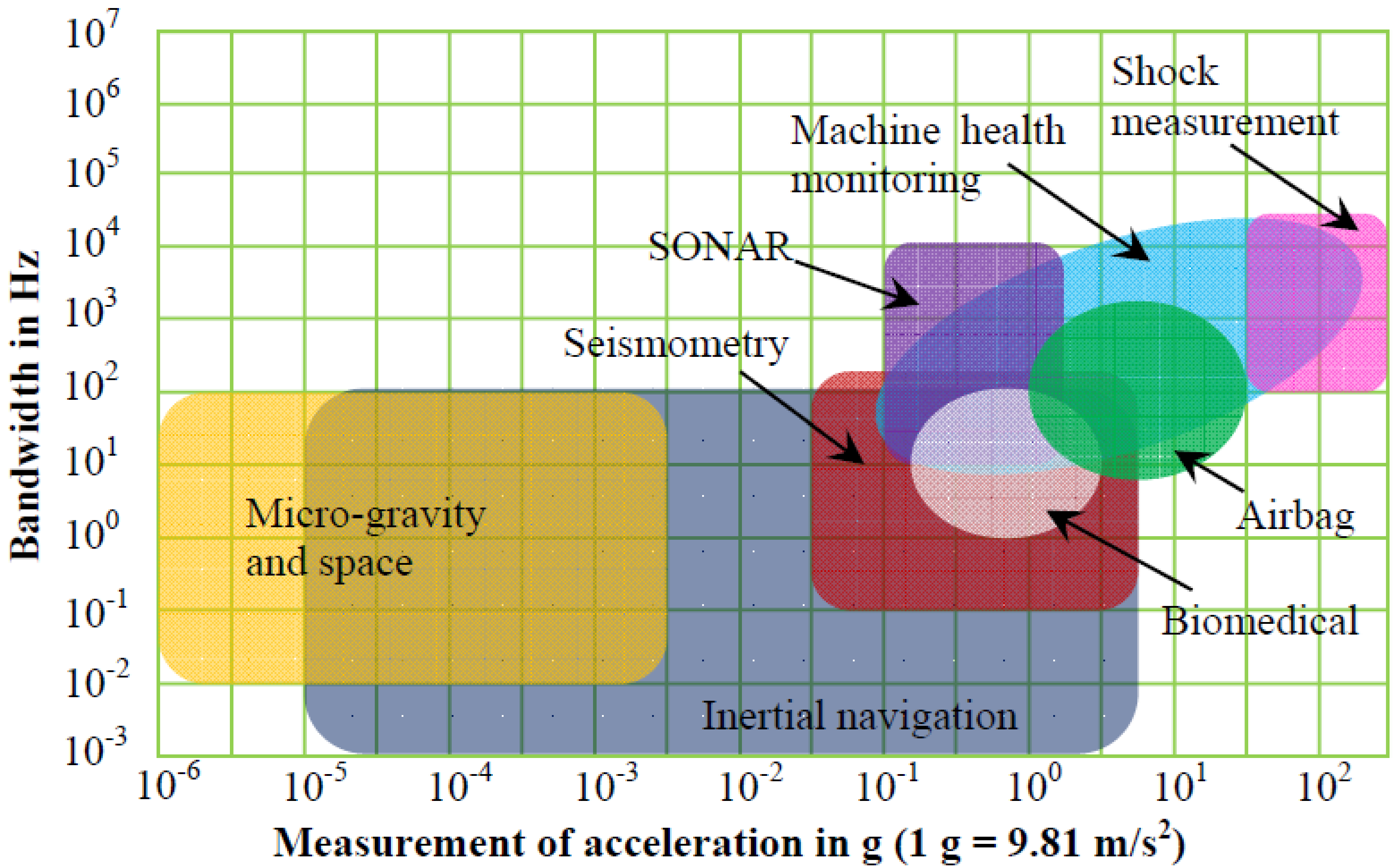
} Usually, tradeoff is necessary.

We try to enhance the sensitivity without compromising the bandwidth.

Specifications of an accelerometer

- Sensitivity
- Bandwidth
- Resolution
- Range
- Time constant
- Quality factor

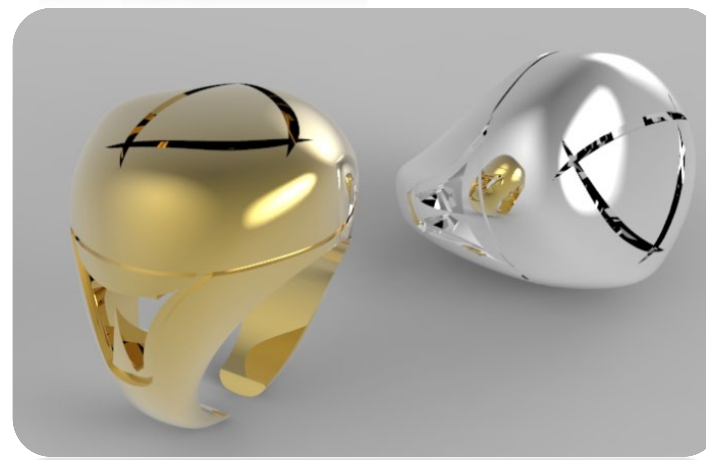
Accelerometer applications



Applications in consumer products

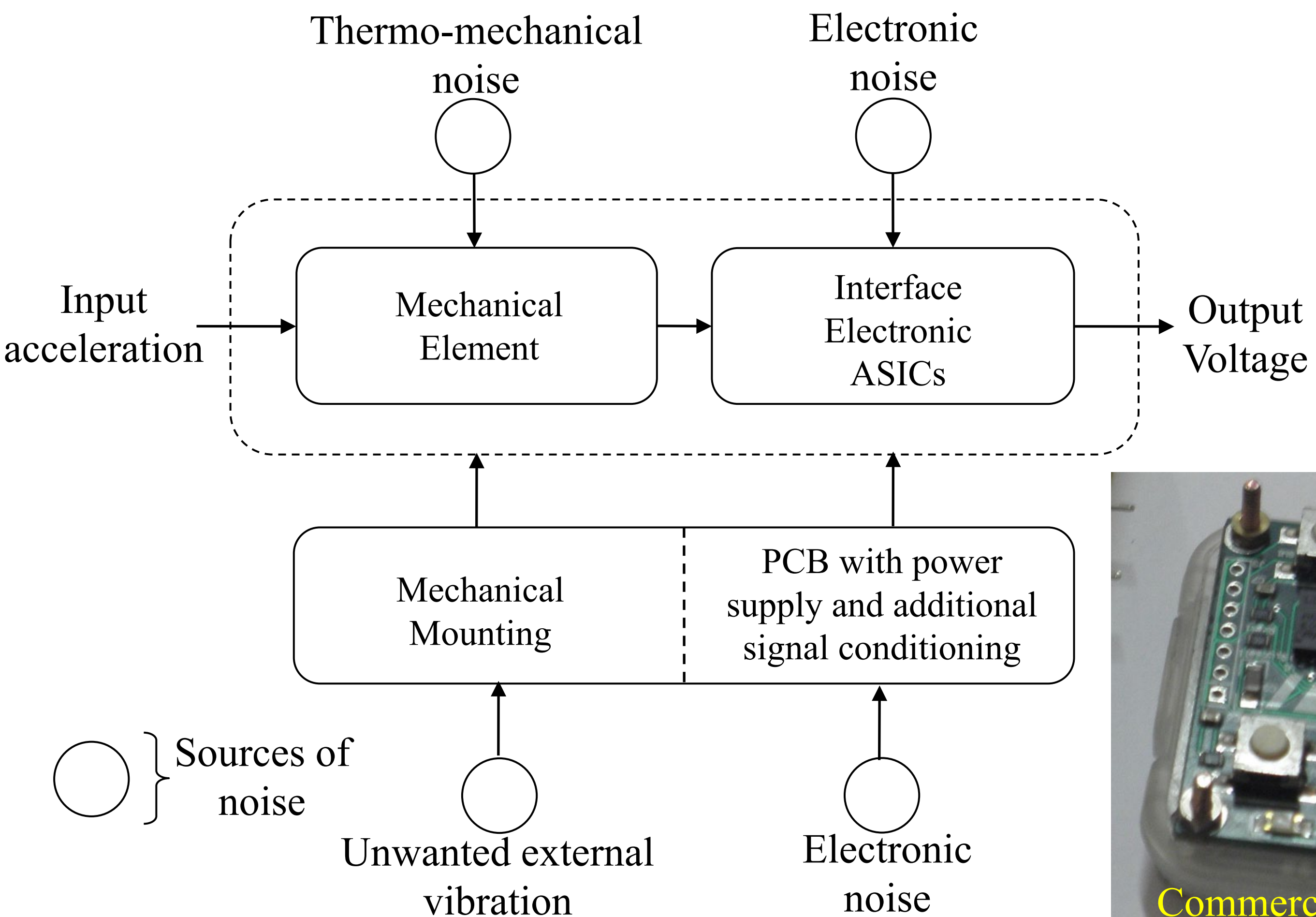
- Mobile phones
- Laptops
- Wearable sensors
- Toys

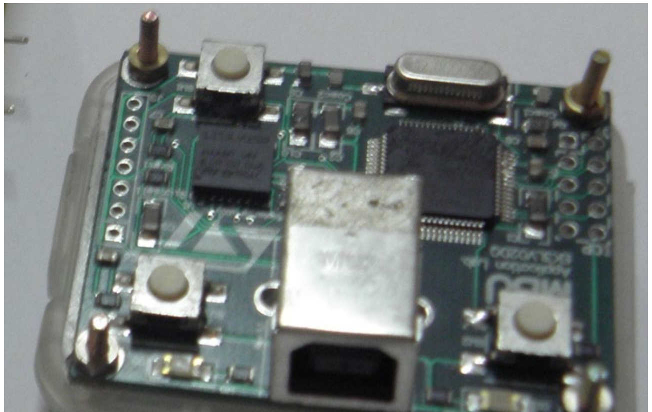
Cognitive Jewellery



Saxena, Rao, Ananthasuresh, 2013

Block diagram of a micromachined accelerometer device





Commercial Accelerometer with integrated electronics on a PCB

Noise in capacitive accelerometers

❑ Mechanical-thermal noise or Brownian Noise per $\sqrt{Hz}$

$$BNEA = \frac{\sqrt{4K_B TD}}{M} = \sqrt{\frac{4K_B T\omega_0}{QM}}$$

Could be as small as ~ 100 ng/√Hz

❑ Interface electronic noise or Circuit noise (Johnson's noise, 1/f noise, Shot noise, Generation and recombination noise, external interferences etc.)

$$CNEA = \frac{\Delta C_{\min}}{S} \left[\frac{m/s^2}{\sqrt{Hz}}\right]$$

Could be of the order of 1-10 µg/√Hz

$\Delta C_{\min}$ is the minimum detectable capacitance per $\sqrt{Hz}$

S is the capacitance sensitivity of the interface electronics $(\Delta C/g)$

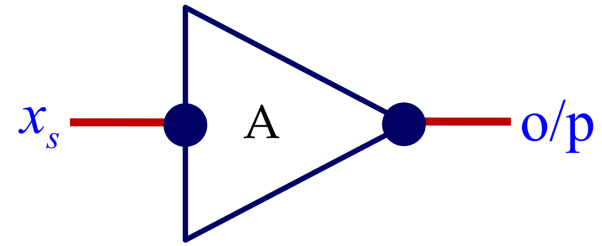
❑ Total noise floor in an accelerometer device

$$TNEA = \sqrt{(BNEA)^2 + (CNEA)^2} \left[\frac{m/s^2}{\sqrt{Hz}}\right]$$

❑ Therefore, CNEA >> BNEA and TNEA is dominated by CNEA

Mechanical Amplification – Why?

- Enhance the mechanical sensitivity by incorporating a mechanical amplifier to the accelerometer without increasing the noise-floor significantly.



x_s is the acceleration signal

n_m is the mechanical noise (BNEA)

n_e is the electronics noise (CNEA)

$\} \; n_e > n_m$

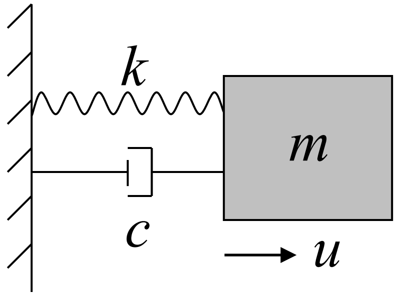
A is the gain achieved either by mechanical means or using electronic amplifiers

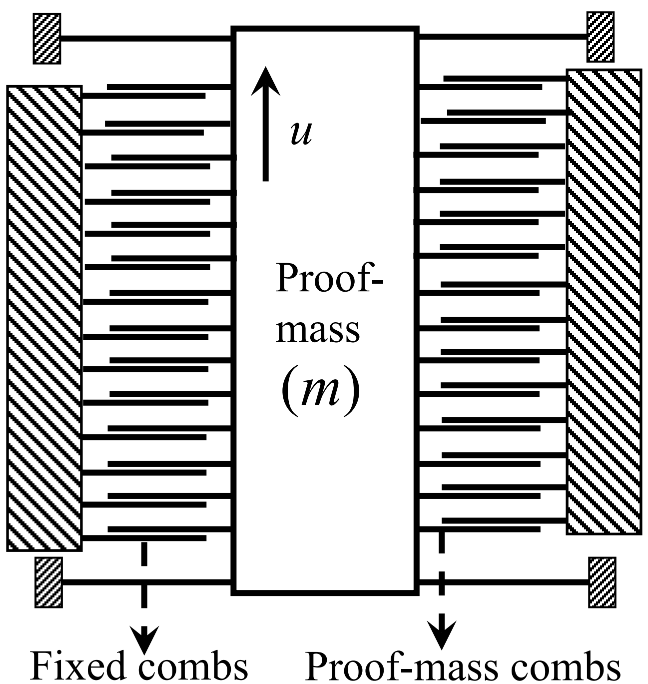
$$SNR_{MA} = \frac{Ax_s}{An_m + n_e} \qquad SNR_{EA} = \frac{Ax_s}{n_m + An_e}$$

$$\therefore SNR_{MA} \gg SNR_{EA}$$

- Technical premise of our work: **Mechanical Amplification**
- For mechanical amplification, **Displacement-amplifying Compliant Mechanisms (DaCMs)** are used.

Sensitivity of an capacitive accelerometer





Conventional micromachined capacitive accelerometer

$$\frac{\Delta V}{g} = K\left(\frac{\Delta C}{g}\right) = K\left(\frac{2uC_{\text{base}}}{gd_0}\right) = K\left(\frac{2amC_{\text{base}}}{gd_0 k}\right)$$

where,

ΔC is the change in capacitance

K is the circuit gain

u is the displacement of the proof-mass

a is the applied acceleration

m is the mass of the proof-mass

C_{base} is the rest capacitance of the sense-comb

d_0 is the sense gap

k is the suspension stiffness

Ways to increase sensitivity and trade-off therein

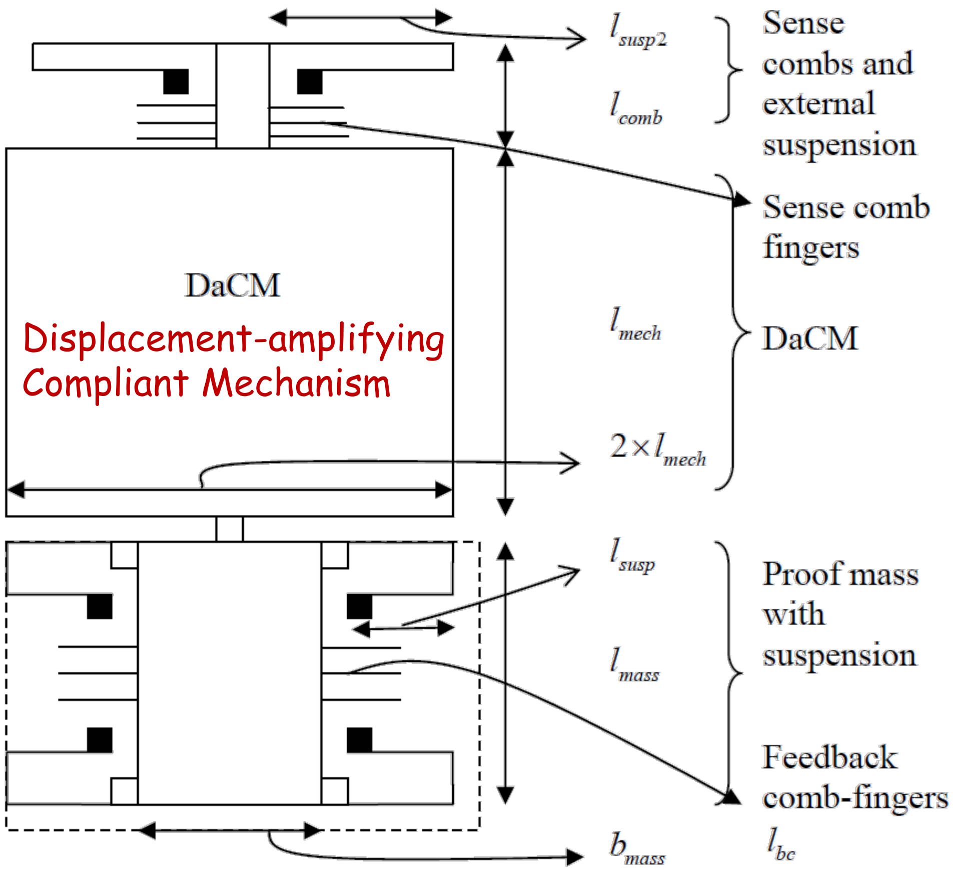
Sensitivity of an accelerometer

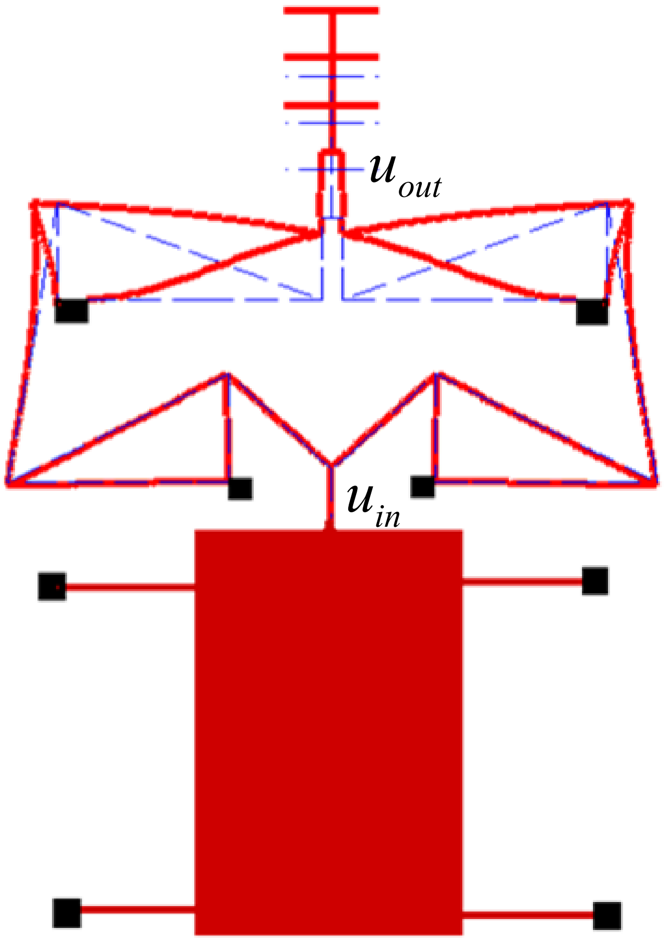
$$\frac{\Delta V}{g} = K\left(\frac{\Delta C}{g}\right) = K\left(\frac{2uC_{\text{base}}}{gd_0}\right) = K\left(\frac{2amC_{\text{base}}}{gd_0k}\right)$$

- Increase circuit gain
  - Signal-to-noise ratio is not good.
- Large mass
  - Out-of-plane sensitivity becomes a problem
  - Complexity in fabrication
  - Low bandwidth
- Low stiffness of the suspension
  - Low bandwidth
- Low damping
  - Only in conjunction with high sensitivity
  - Complexity in packaging and testing
- Small gap in capacitive sense-combs
  - Complexity in fabrication
  - Low range

Mechanical amplification

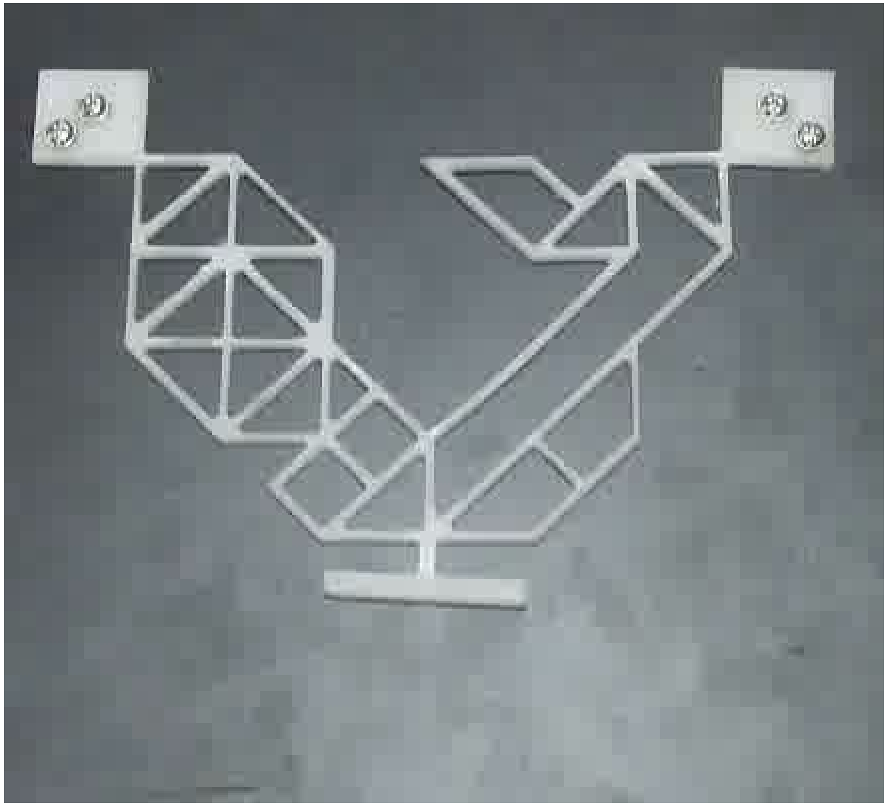
Krishnan and Ananthasuresh, 2006



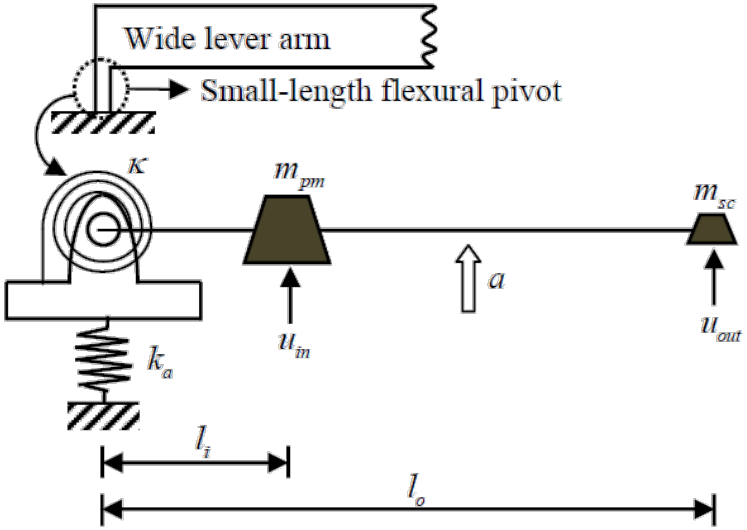


Geometric Amplification $n = \dfrac{u_{out}}{u_{in}}$

DaCM for mechanical amplification
(Displacement-amplifying Compliant Mechanism)



How about a simple lever?

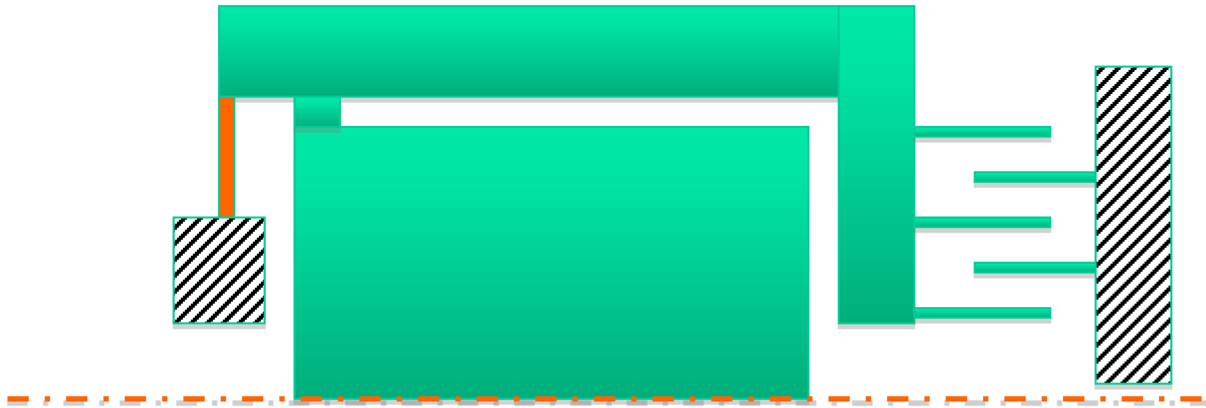


We are interested in the sense-comb displacement (u_{out})

$$u_{out} = \frac{(m_{pm} + m_{sc})a}{k_a} + \frac{l_i l_o \left(m_{pm} + \frac{l_o}{l_i} m_{sc} \right) a}{\kappa}$$

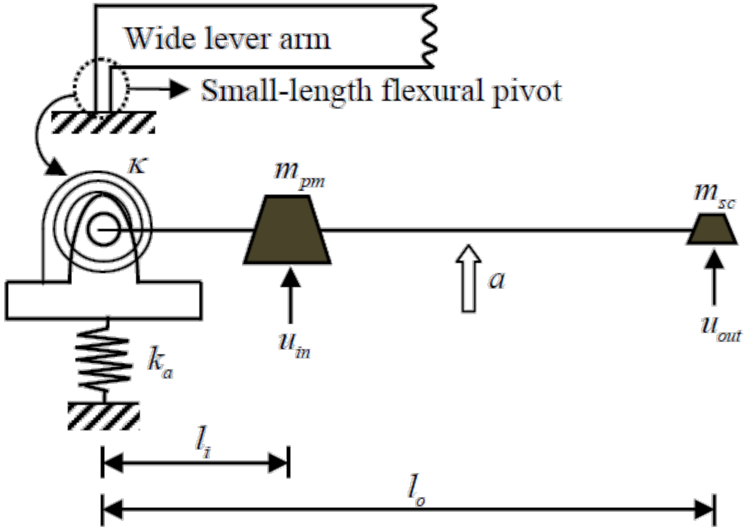
$$\kappa = \frac{EI}{L}$$

$$k_a = \frac{EA}{L}$$



Ref: I. Zeimpekis, I. Sari, and M. Kraft, "Characterization of a Mechanical Motion Amplifier Applied to a MEMS Accelerometer", in *Journal of Microelectromechanical Systems*, Vol.21, Issue. 5, pp. 1032 – 1042, October 2012.

How about a simple lever?

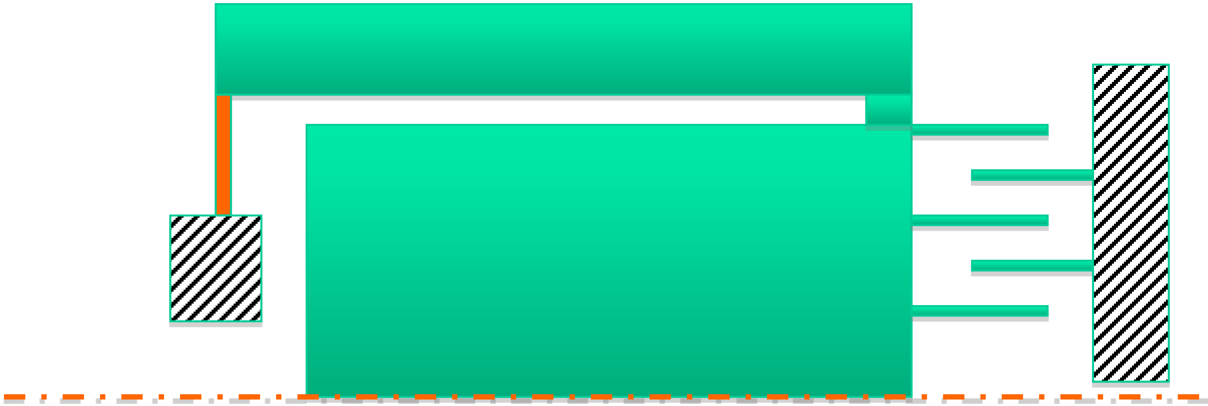


We are interested in the sense-comb displacement (u_{out})

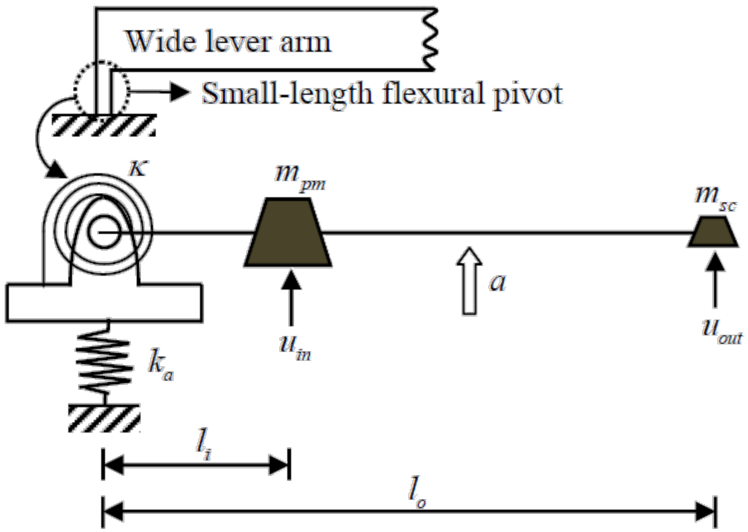
$$u_{out} = \frac{(m_{pm} + m_{sc})a}{k_a} + \frac{l_i l_o \left(m_{pm} + \frac{l_o}{l_i} m_{sc} \right) a}{\kappa}$$

$$\kappa = \frac{EI}{L}$$

$$k_a = \frac{EA}{L}$$



How about a simple lever?



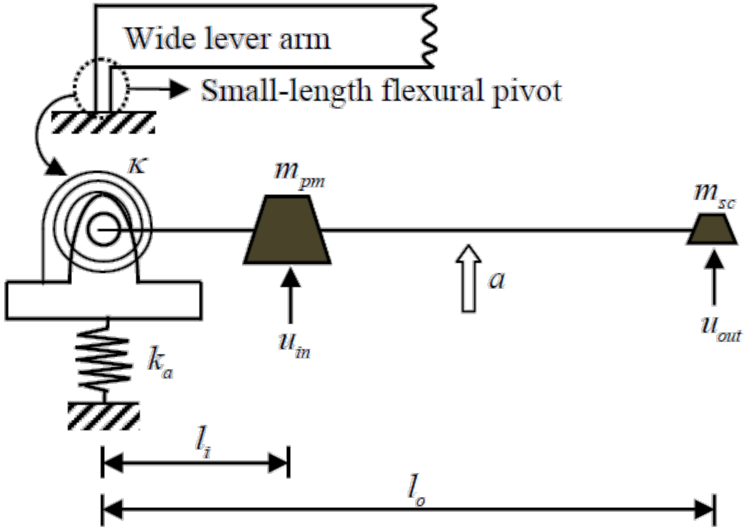
We are interested in the sense-comb displacement (u_{out})

$$u_{out} = \frac{(m_{pm} + m_{sc})a}{k_a} + \frac{l_i l_o \left(m_{pm} + \frac{l_o}{l_i} m_{sc} \right) a}{\kappa}$$

$$\kappa = \frac{EI}{L}$$

$$k_a = \frac{EA}{L}$$

How about a simple lever?

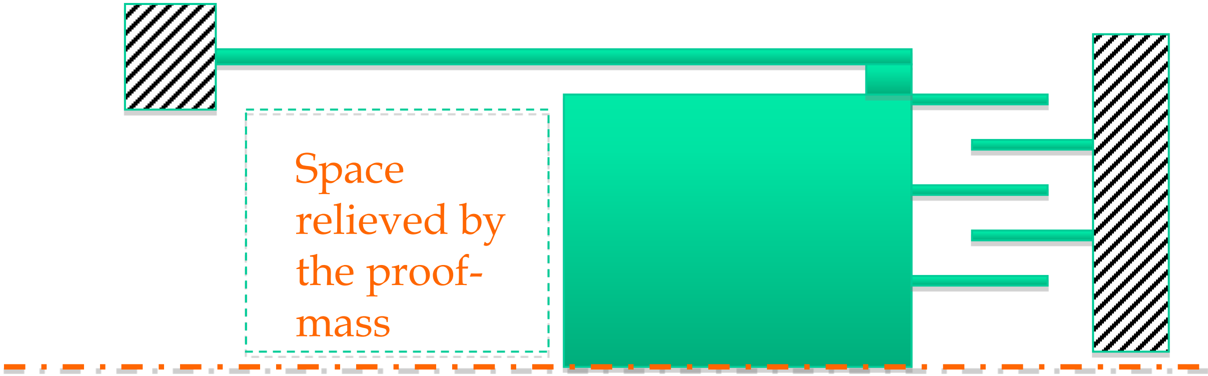


We are interested in the sense-comb displacement (u_{out})

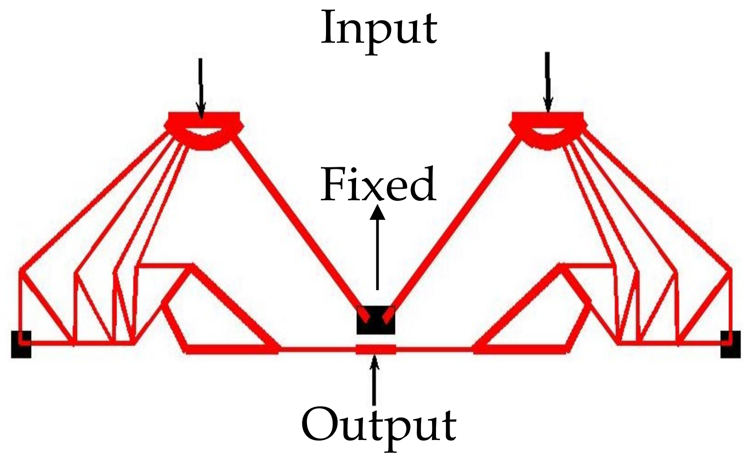
$$u_{out} = \frac{(m_{pm} + m_{sc})a}{k_a} + \frac{l_i l_o \left(m_{pm} + \frac{l_o}{l_i} m_{sc} \right) a}{\kappa}$$

$$\kappa = \frac{EI}{L}$$

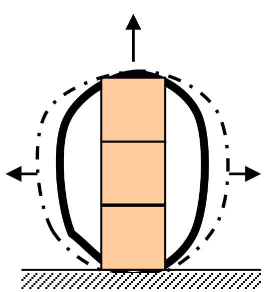
$$k_a = \frac{EA}{L}$$



Displacement-amplifying Compliant Mechanisms (DaCMs)

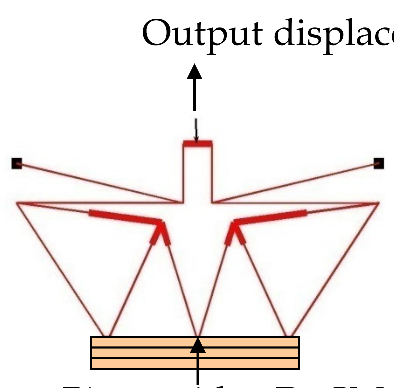


- Equivalent to mechanical levers without any joints.
- Use elastic strain energy for amplification of input displacement.
- Used for amplifying displacements of piezo-electric stacks for micro-positioning.



Elliptical amplifier

Robbins et al., 1990



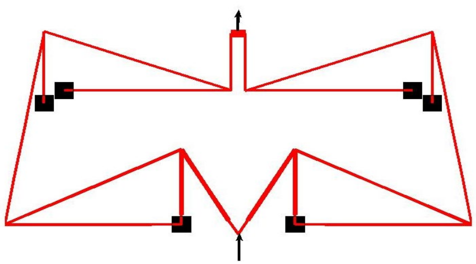
Piezo with a DaCM

Hetrick and Kota, 2000

DaCMs have been used previously for actuator applications only.

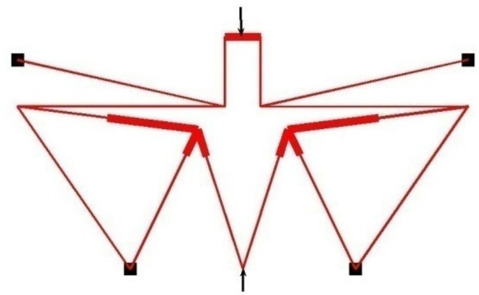
Mechanism options…many, many.

M1



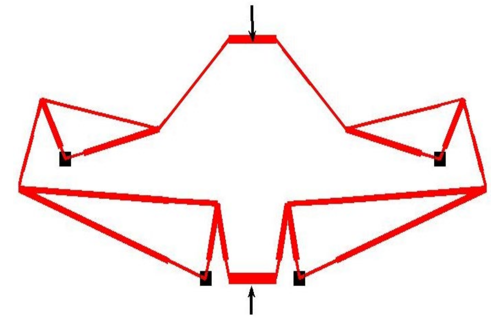
Hetrick, Kota, 1999

M2



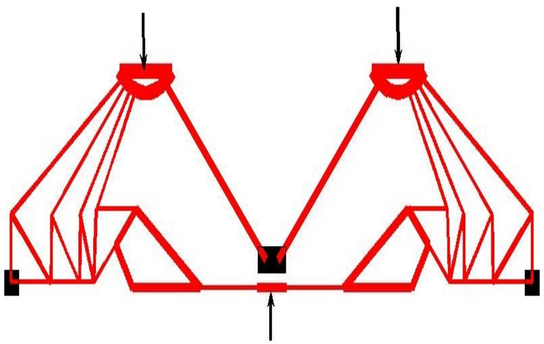
Hetrick, Kota, 2000

M3

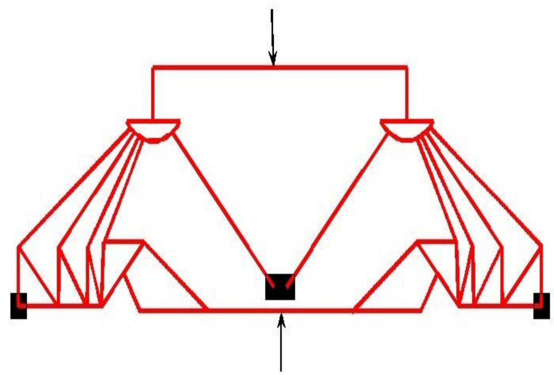


Hetrick, Kota, 1998

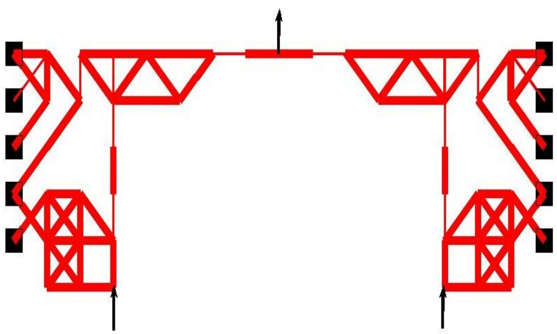
M4



M5



M6



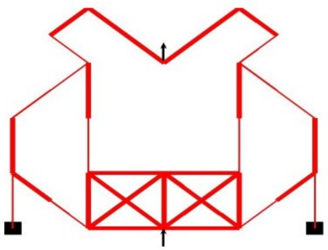
Canfield and Frecker, 2000

Saxena and Ananthasuresh, 2000 ;

Yin and Ananthasuresh, 2003

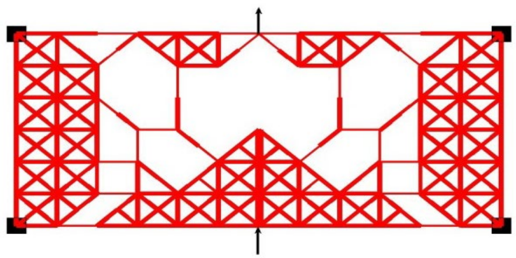
Mechanisms options… many, many

M7



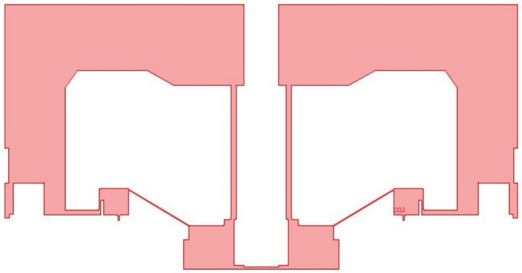
Maddisetty, Frecker, 2001

M8



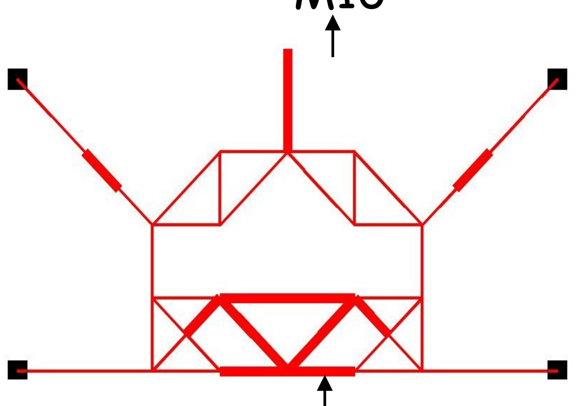
Optimized with cross-axis constraints by Girish Krishnan, Ananthasuresh

M9



Du et al., 2000

M10

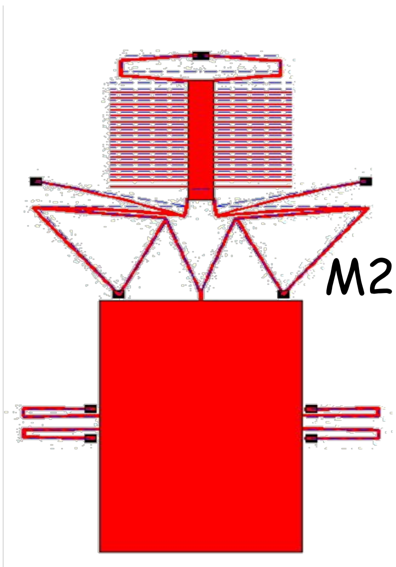


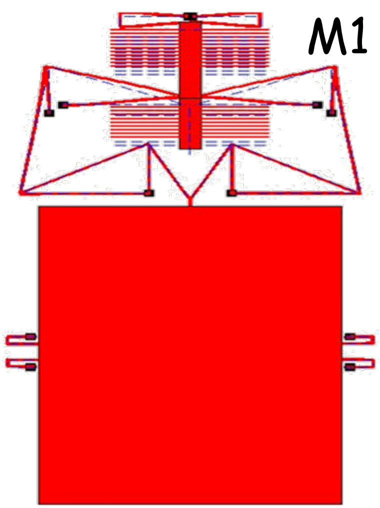
Topology optimization to obtain a high *NA* and low cross-axis sensitivity

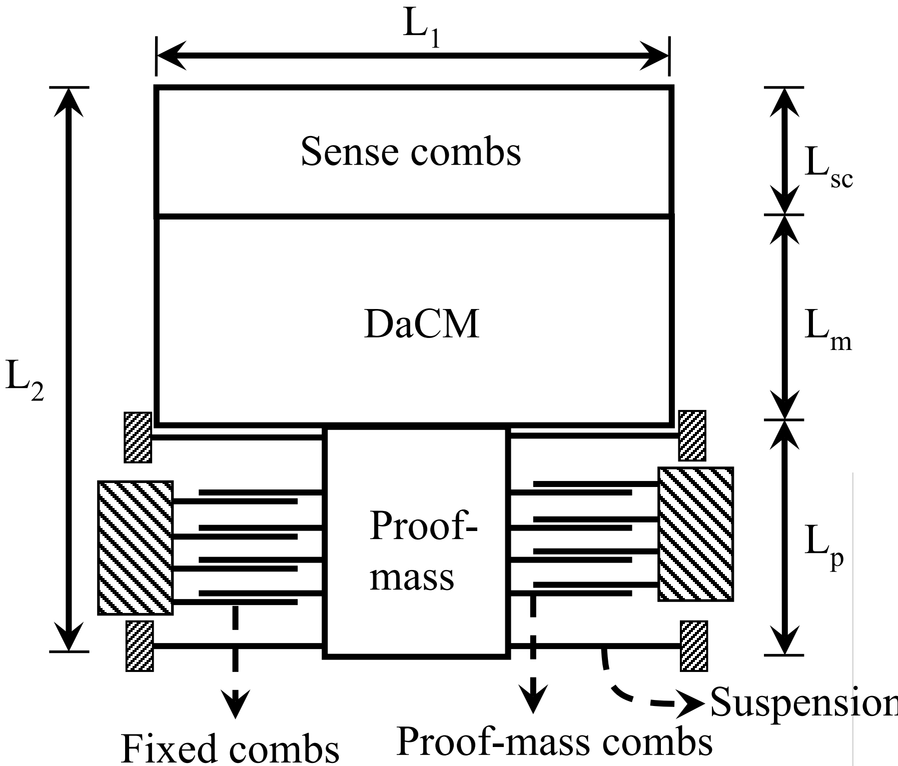
Attributes for comparison

- Net Amplification factor (NA)
- Maximum Stress before failure (FS)
- Natural Frequency (f)
- Cross axis stiffness (k_{cross})

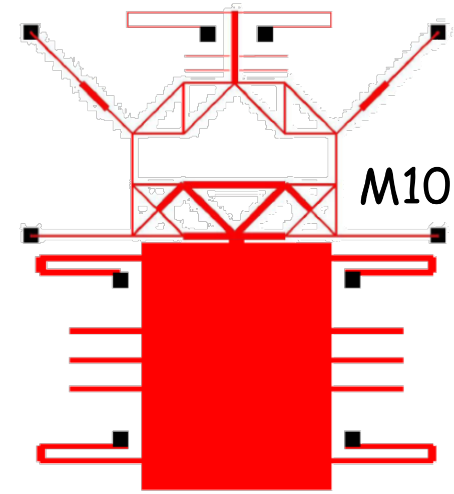
Single-axis in-plane Accelerometer designs with DaCMs

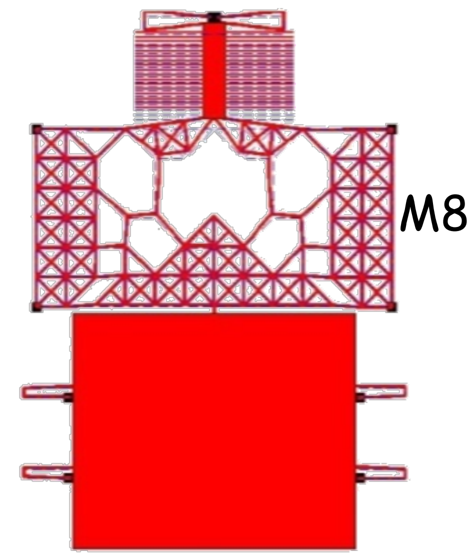






Accelerometers with DaCMs



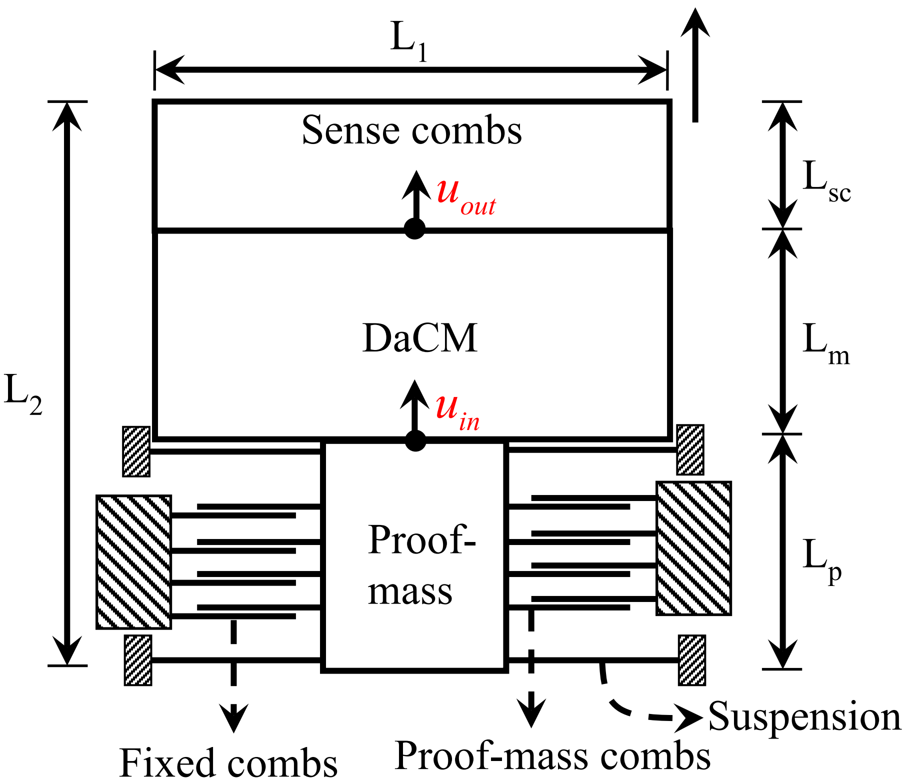


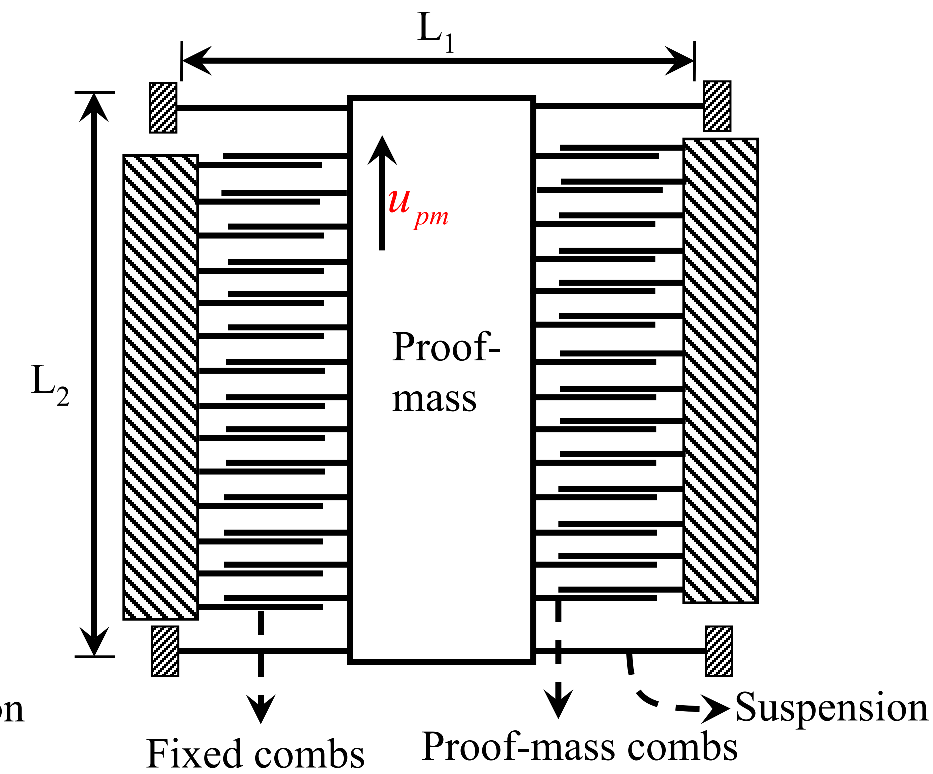
Re-design of the DaCMs are required in order to achieve high value of NA and *n*

Let us learn to design a DaCM

(using instant centre method—a graphical design method.

Geometric Amplification, Net Amplification and figure of merit (FoM)





Area = $L_1 L_2$

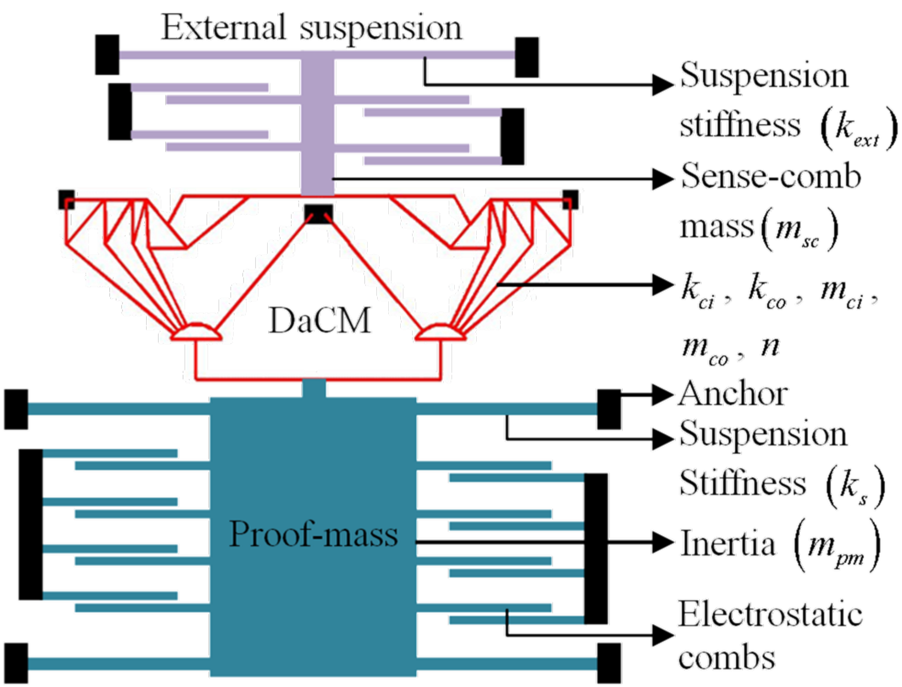
Area = $L_1 L_2$

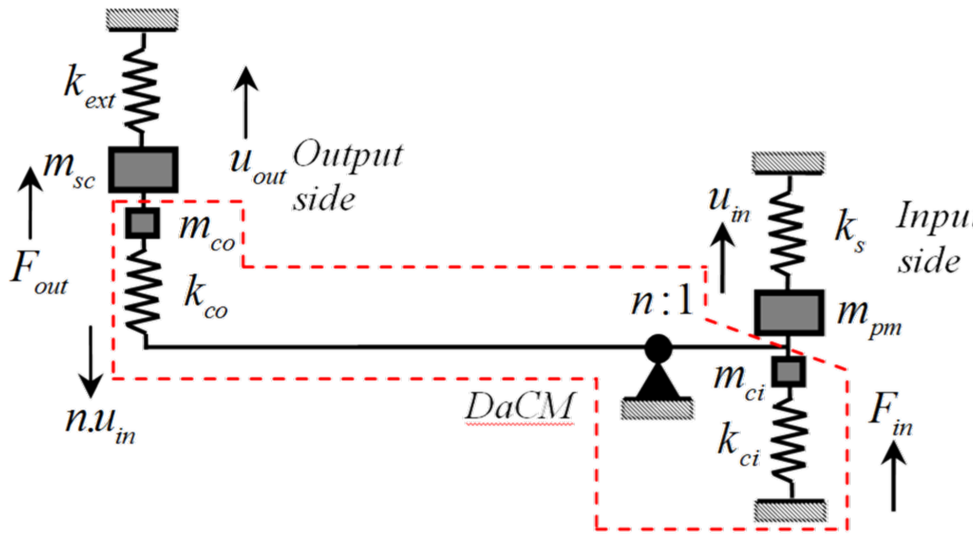
Geometric Amplification (n) = $\dfrac{u_{out}}{u_{in}}$

Net Amplification (NA) = $\dfrac{u_{out}}{u_{pm}}$

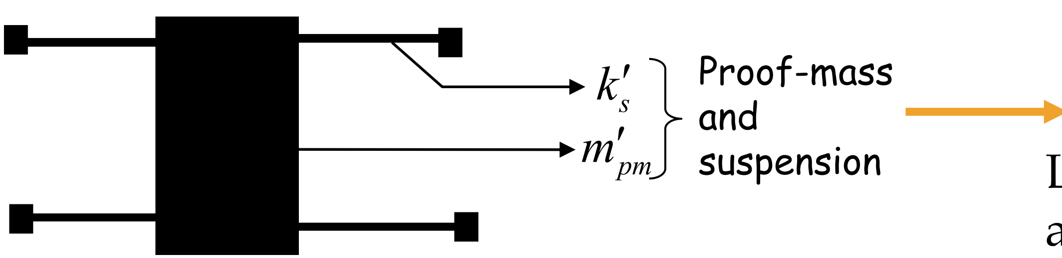
Figure of Merit (FoM) = $\left(\dfrac{u}{g}\right)\omega_0^{\,2} = 4\pi^2\left(\dfrac{u}{g}\right)f_0^{\,2}$

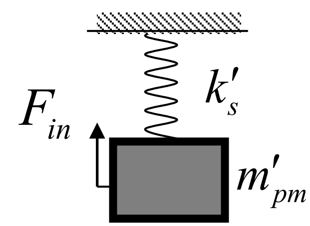
Equivalent lumped parameter model





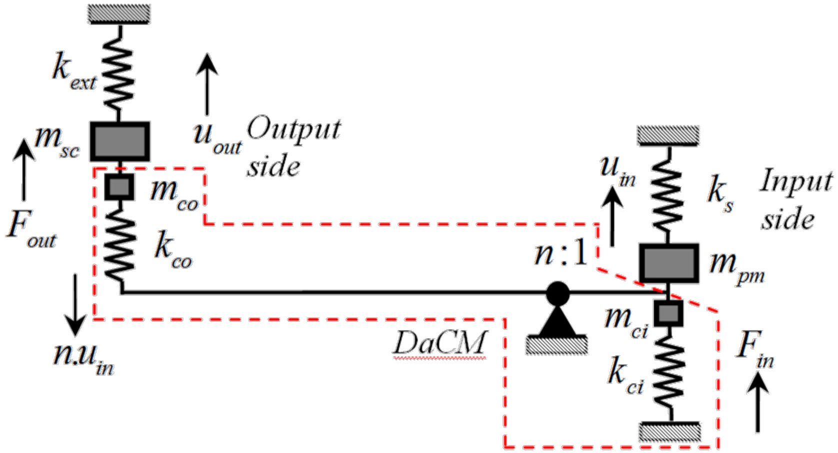
Lumped parameter model of an accelerometer with a DaCM



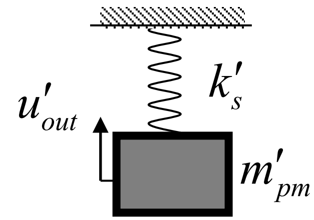


Lumped parameter model of an accelerometer without a DaCM

Equivalent lumped parameter model



Lumped parameter model of an accelerometer with a DaCM



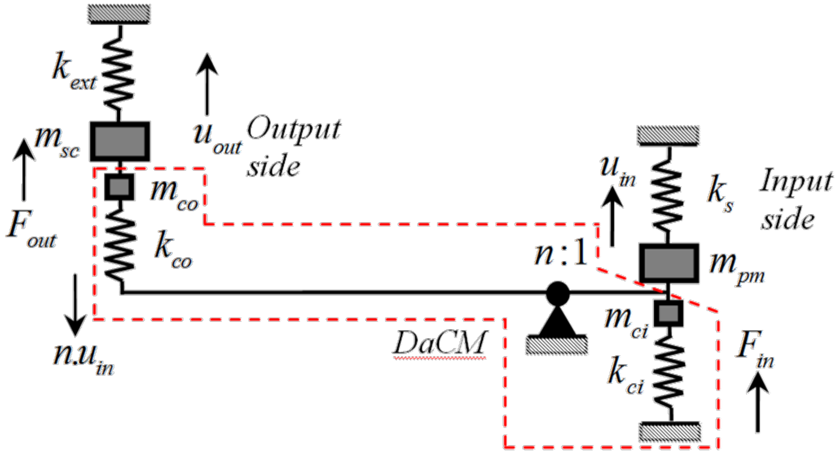
Lumped parameter model of an accelerometer without a DaCM

$$u_{out} = \frac{\left(nk_{co}m_{pm} + m_{sc}k_{ci} + m_{sc}k_s + n^2 m_{sc}k_{co}\right)a}{\left(k_{co}k_{ci} + k_{co}k_s + k_{ext}k_{ci} + k_{ext}k_s + n^2 k_{ext}k_{co}\right)}$$

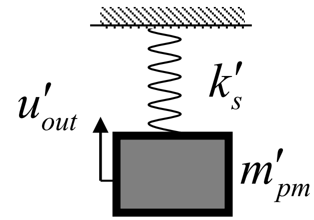
$$u'_{out} = m'_{pm}a / k'_s$$

$$NA = \frac{u_{out}}{u'_{out}} = \frac{\left(nk_{co}m_{pm} + m_{sc}k_{ci} + m_{sc}k_a + n^2 m_{sc}k_{co}\right)k'_s}{\left(k_{co}k_{ci} + k_{co}k_s + k_{ext}k_{ci} + k_{ext}k_s + n^2 k_{ext}k_{co}\right)m'_{pm}}$$

Equivalent lumped parameter model



Lumped parameter model of an accelerometer with a DaCM



Lumped parameter model of an accelerometer without a DaCM

$$f_0 = \frac{1}{2\sqrt{2}\pi}\sqrt{(\alpha+\beta)-\sqrt{\left((\alpha-\beta)^2+\gamma\right)}}$$

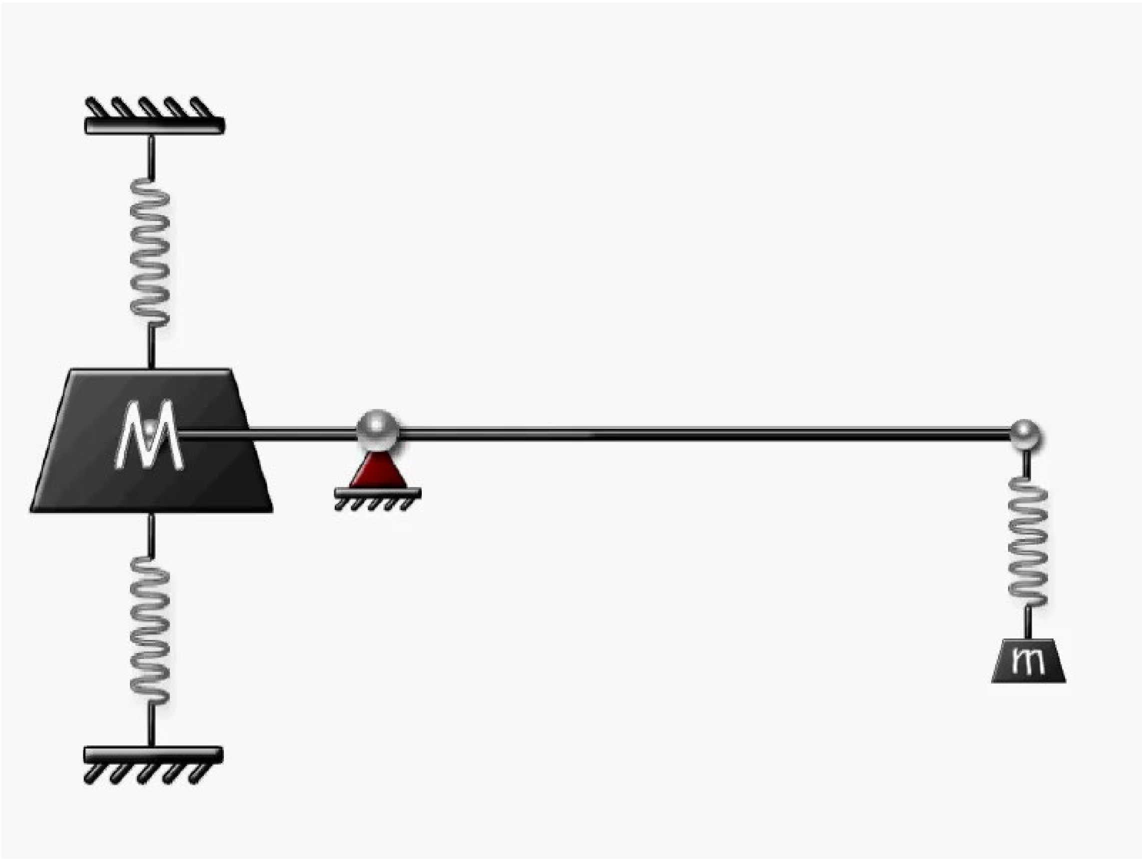
$$f'_0 = \frac{1}{2\pi}\sqrt{\frac{k'_s}{m'_{pm}}}$$

Where,

$$\alpha = \frac{\left(k_{ci}+k_s+n^2k_{co}\right)}{\left(m_{ci}+m_{pm}\right)};\ \beta = \frac{\left(k_{co}+k_{ext}\right)}{\left(m_{co}+m_{sc}\right)};$$

$$\gamma = \frac{4n^2k_{co}^2}{\left(m_{ci}+m_{pm}\right)\left(m_{co}+m_{sc}\right)}$$

Amplification or Transformation?



Different from amplification.....

It is displacement transformation as only the displacement gets amplified, not the power.

Two Case studies

- ❑ Comparisons were made with the two most sensitive single-axis capacitive accelerometers from the literature with their modified designs with DaCMs.

- ❑ Footprint of the accelerometers from the literature and their modified designs were kept the same.

- ❑ Existing DaCMs were re-designed and optimized for those accelerometers using a stiffness map-based method developed by *Hegde and Ananthasuresh 2011*.

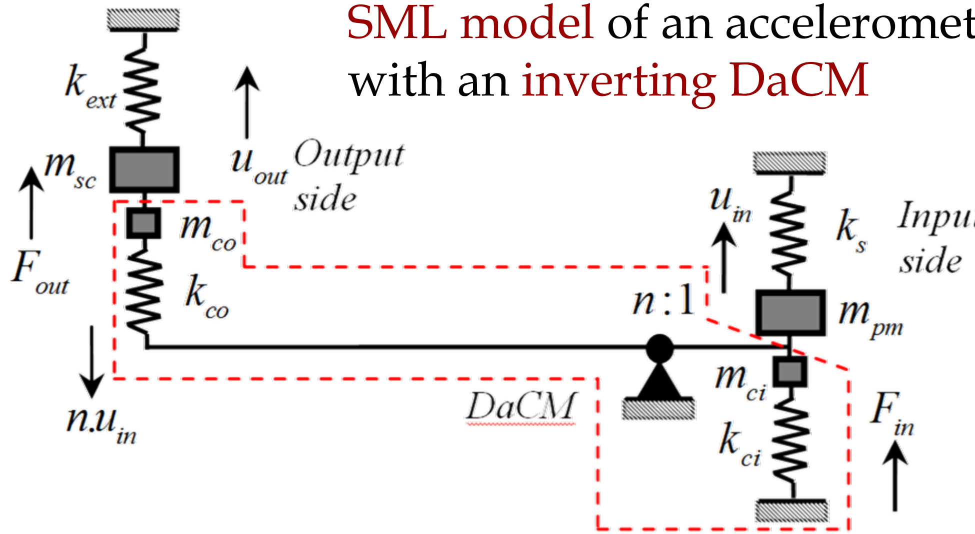
- ❑ Static displacement sensitivity, resonance frequency and the Figure of Merit (FoM) of designs with and without DaCMs were compared.

Selection and re-design of a DaCM using stiffness map-based method

$$F_{inL} \le F_{in} \le F_{inH}$$
$$u_{inL} \le u_{in} \le u_{inH}$$
$$F_{outL} \le F_{out} \le F_{outH}$$
$$u_{outL} \le u_{out} \le u_{outH}$$
$$k_{aL} \le k_a \le k_{aH}$$
$$k_{extL} \le k_{ext} \le k_{extH}$$

$$k_{ci} = \frac{F_{in} - k_a u_{in} - n\left(F_{out} - k_{ext} u_{out}\right)}{u_{in}}$$

$$k_{co} = \frac{\left(F_{out} - k_{ext} u_{out}\right)}{u_{out} - n u_{in}}$$

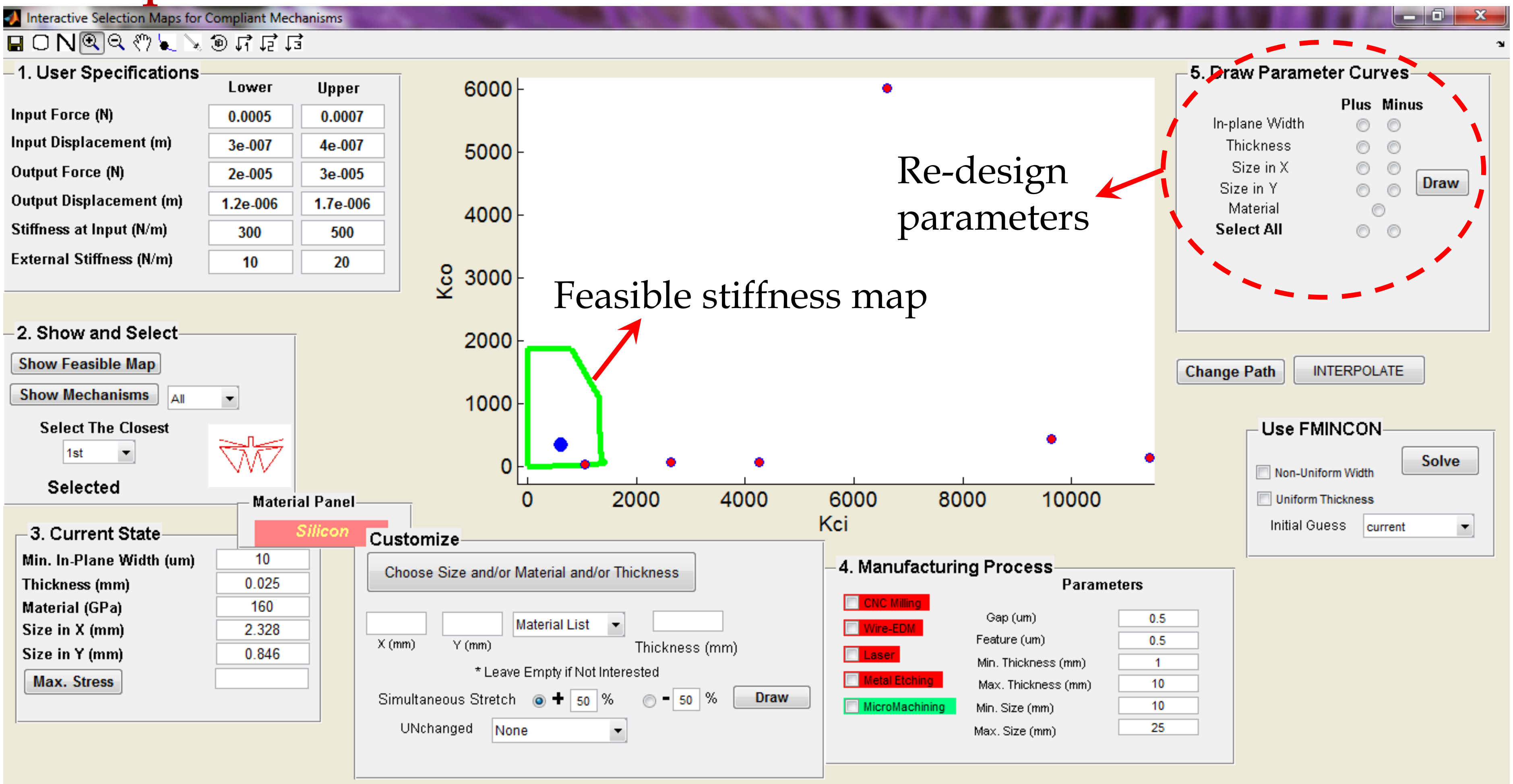


SML model of an accelerometer with an inverting DaCM

Ref: Hegde and Anathasuresh 2011

- Solving six inequalities and the two equilibrium equations, a k_{co} vs. k_{ci} map or the stiffness map is obtained.
- The $k_{co} - k_{ci}$ map is the 2D projection of a feasible volume in the 3D space of $k_{co} - k_{ci} - n$
- Existing DaCMs were plotted as individual points on the stiffness map.
- Method implemented using an interactive MATLAB based program.

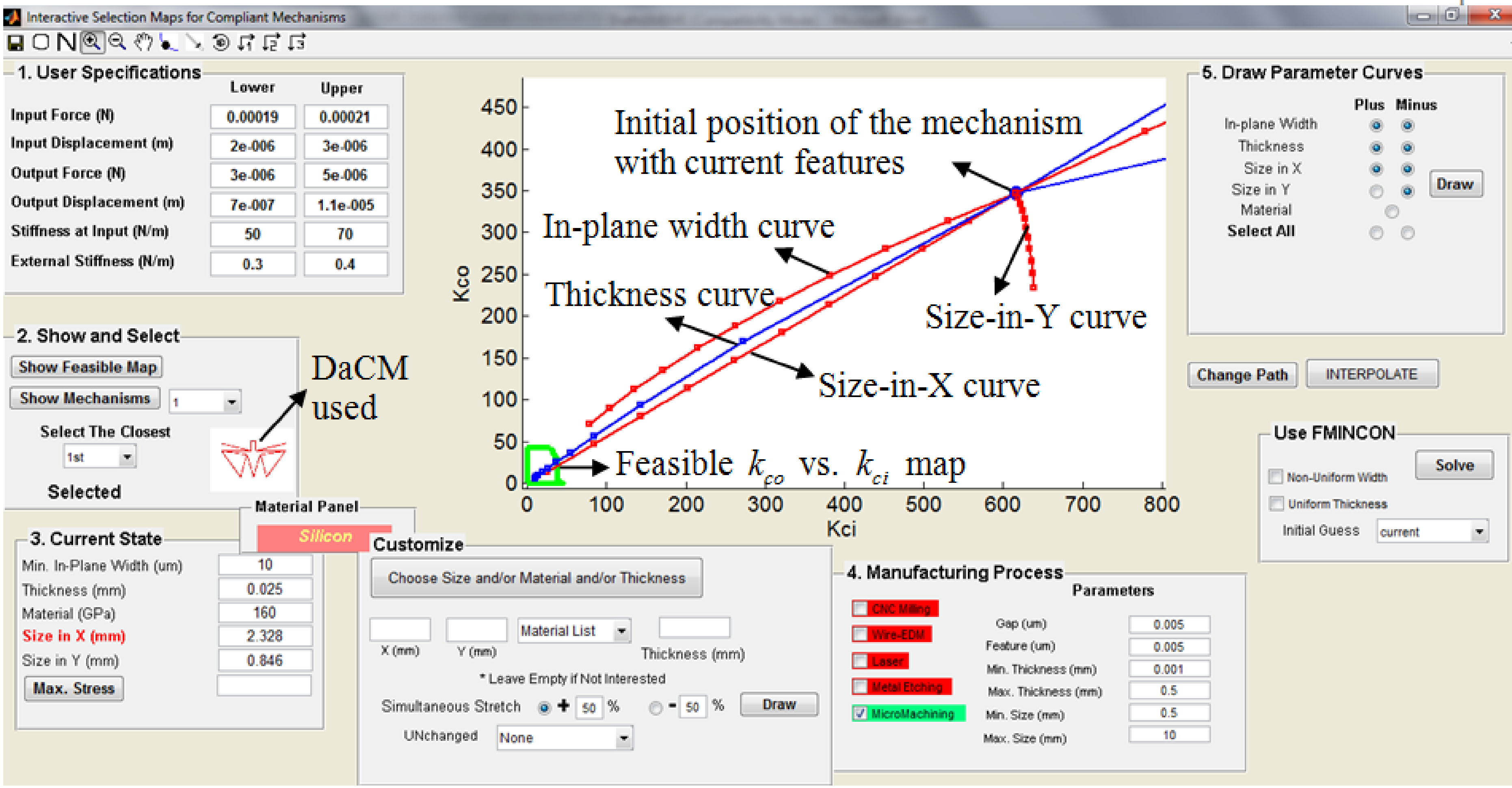
Selection and re-design of a DaCM using stiffness map-based method



Ref: Hegde and Ananthasuresh 2011

Choose any mechanism and bring that inside the feasible stiffness map by varying the re-design parameters.

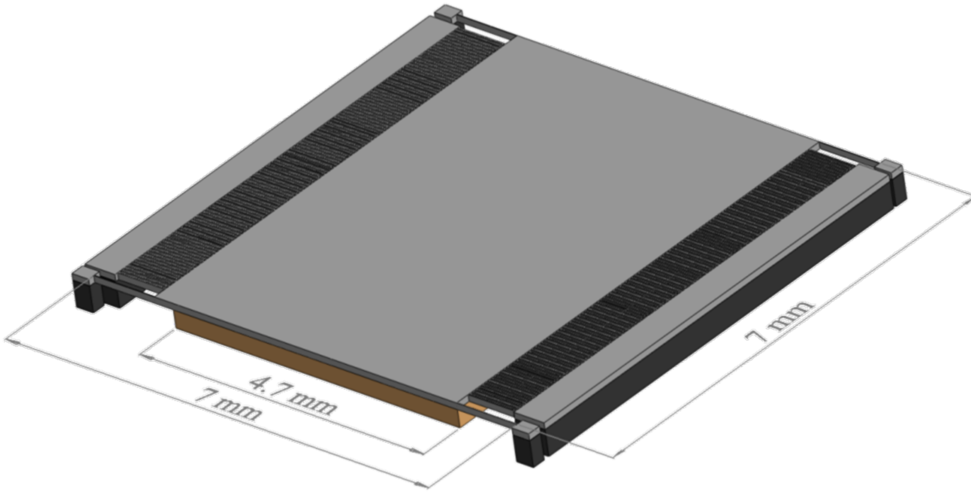
Selection and re-design of a DaCM using stiffness map-based method

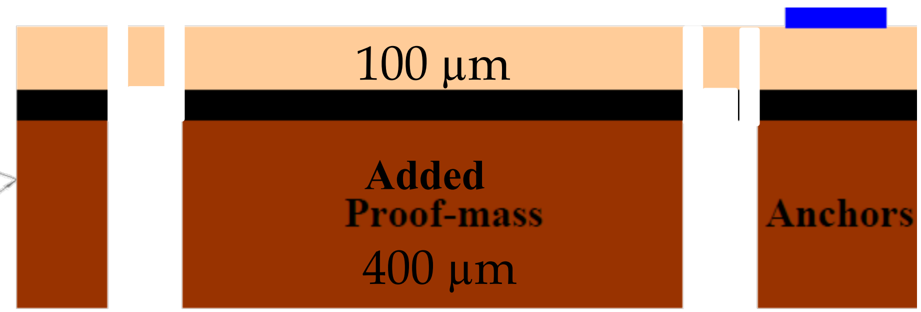


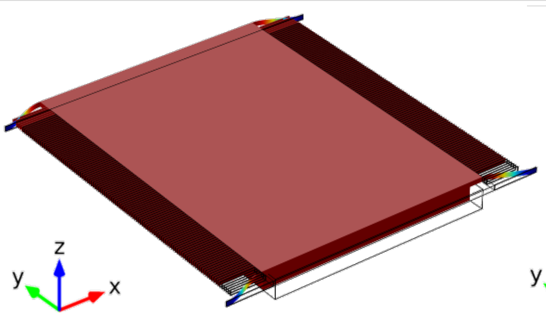
Ref: Hegde and Ananthasuresh 2011

Choose any mechanism and bring that inside the feasible stiffness map by varying the re-design parameters.

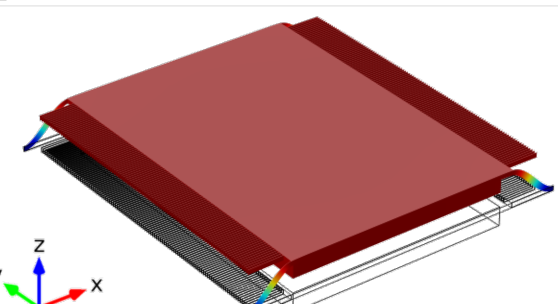
An in-plane capacitive accelerometer by Abdolvand et al. 2007







1st modal frequency ~ 195 Hz



2nd modal frequency ~ 1901 Hz

- 4-5 µm sense-gap achieved by side-wall deposition of polysilicon.
- 38 milli-gram proof-mass
- 110 sense-combs
- First in-plane modal frequency ~ 200 Hz
- Static displacement sensitivity of 6.5 µm/g which corresponds to 30 pF/g capacitance sensitivity.

Modified design of the accelerometer by Abdolvand et al. 2007 using a DaCM

$190\,\mu\text{N} \le F_{in} \le 210\,\mu\text{N}$

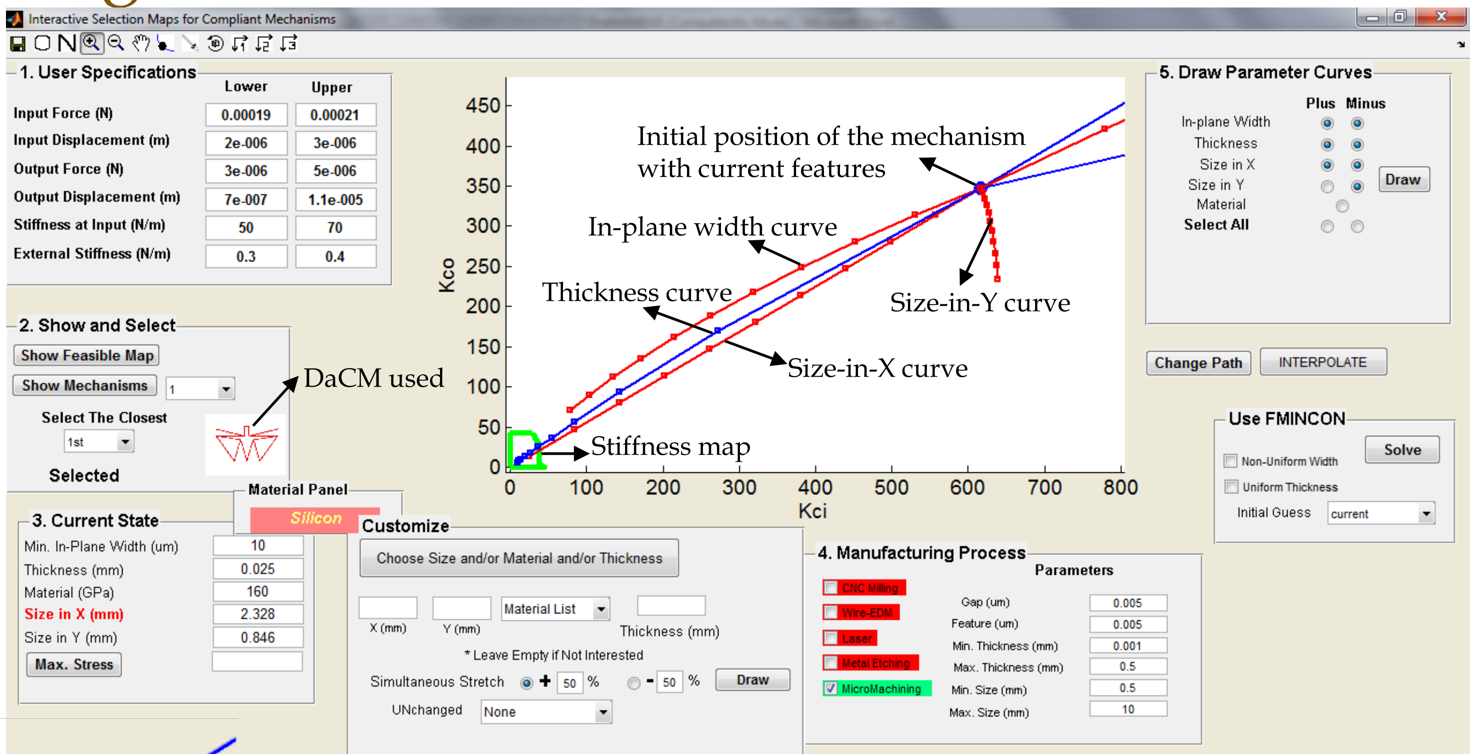
$2\,\mu\text{m} \le u_{in} \le 3\,\mu\text{m}$

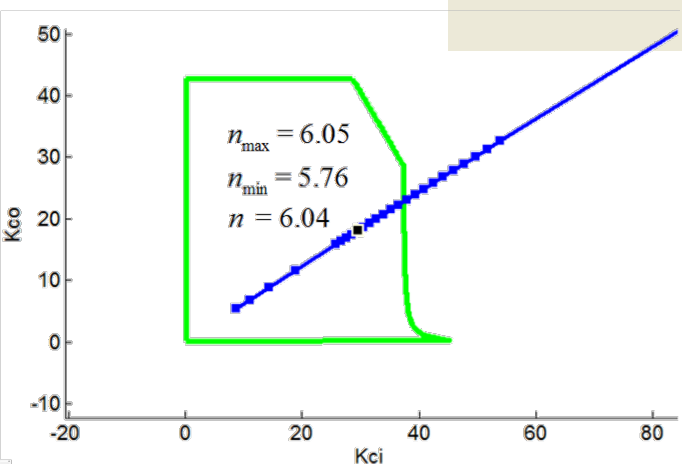
$3\,\mu\text{N} \le F_{out} \le 4\,\mu\text{N}$

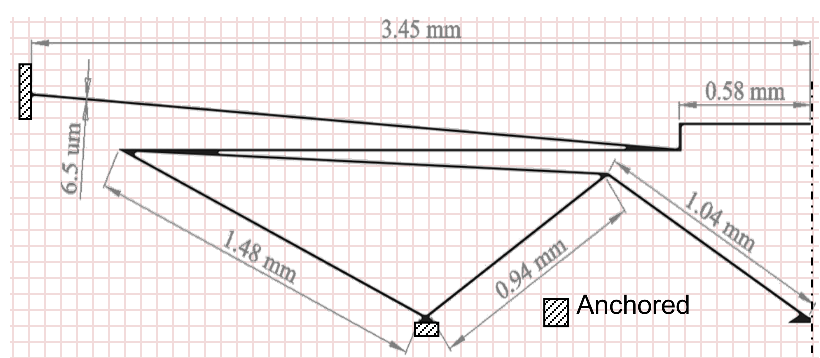
$7\,\mu\text{m} \le u_{out} \le 11\,\mu\text{m}$

$50\,\text{N/m} \le k_s \le 70\,\text{N/m}$

$0.3\,\text{N/m} \le k_{ext} \le 0.4\,\text{N/m}$

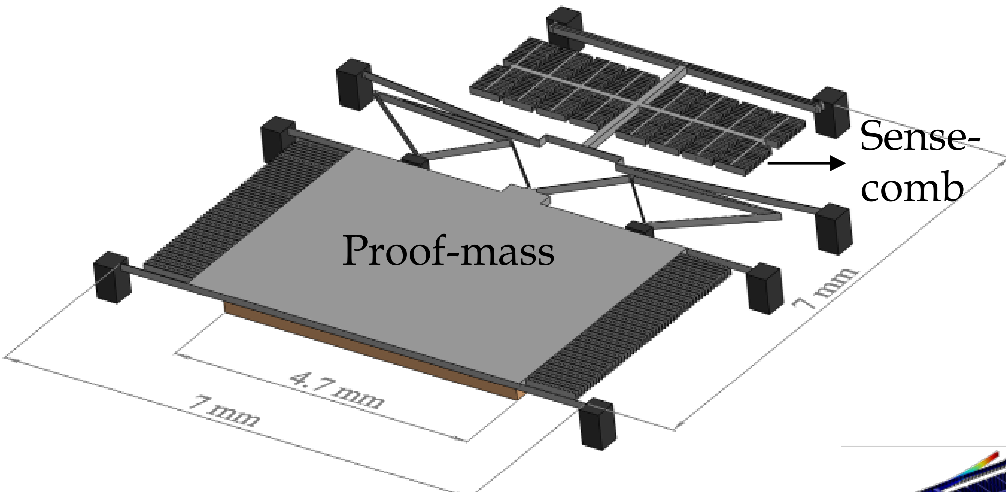




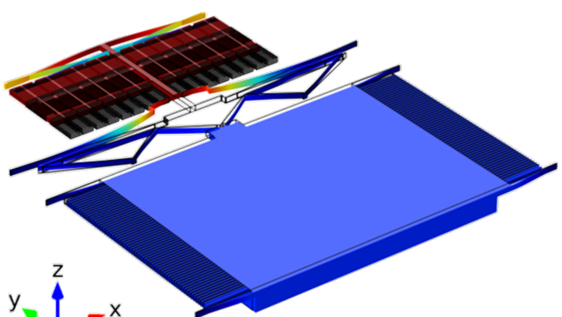


Re-designed and optimized DaCM

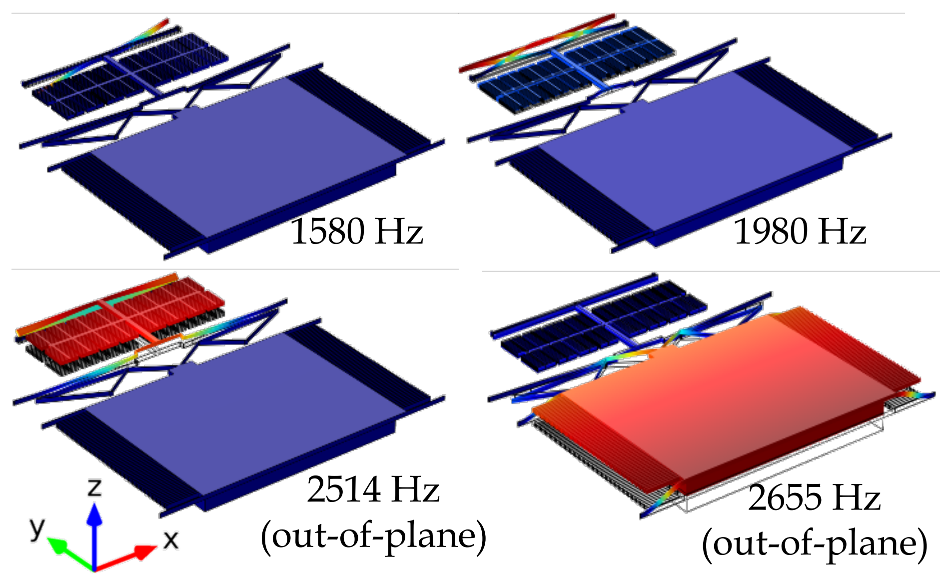
Our modification on Abdolvand et al. 2007 using a DaCM



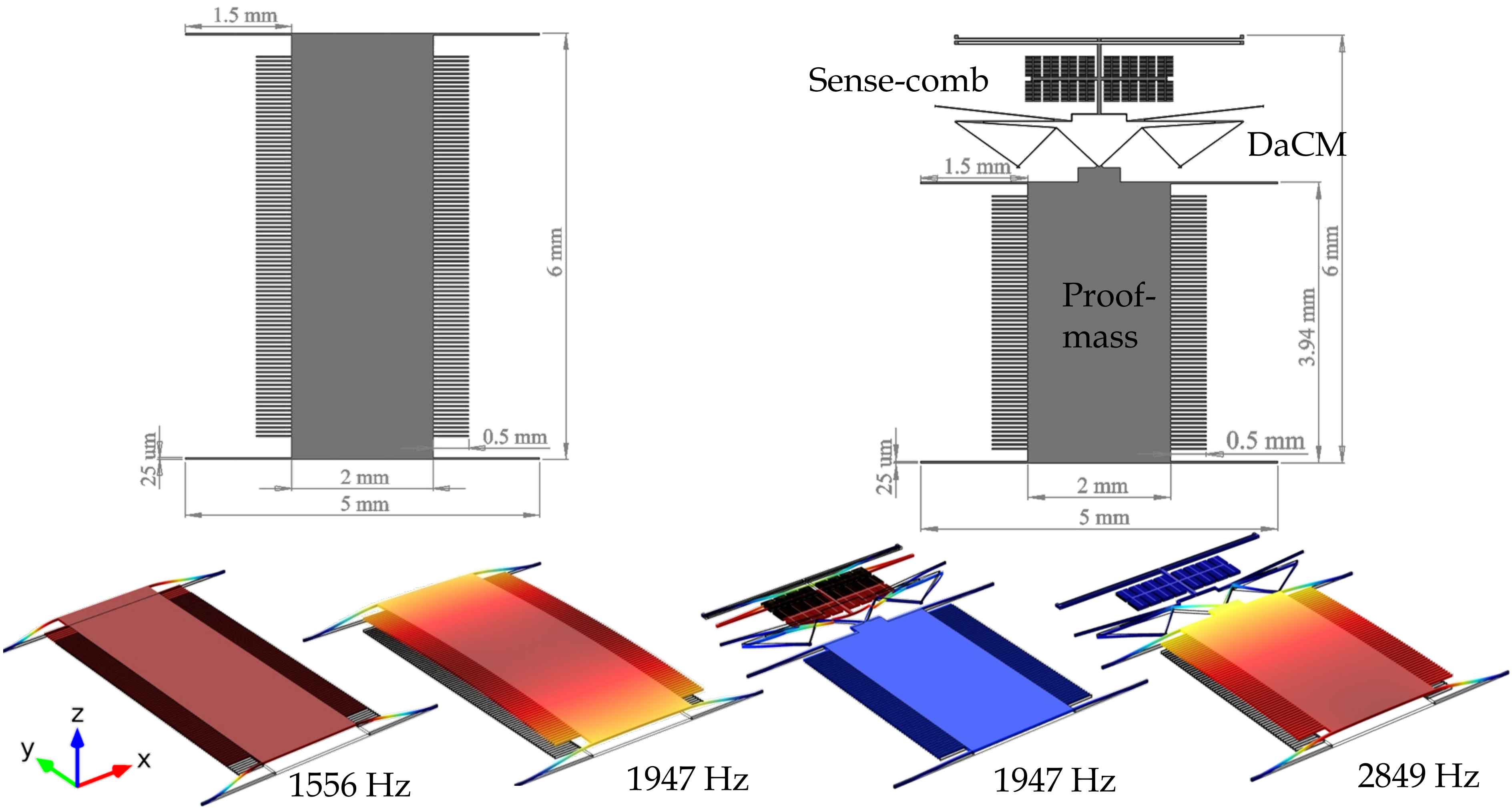
- Same footprint
- Smaller proof-mass 3.9 mm × 5 mm
- Static displacement sensitivity of 10.51 μm/g
- Sensitivity enhancement of 60%
- 1st modal frequency ~ 267 Hz
- 34 % improvement in resonance frequency



1st eigen frequency ~ 267 Hz (in-plane)



Accelerometer by Amini 2006 and our modification



Amini 2006

Our modification

Comparison between the existing accelerometers to the modified designs

Specifications	Accelerometer by Abdolvand et. al. 2007	Modified Design of Abdolvand et al. 2007 using a DaCM	Accelerometer by B. V. Amini 2006	Modified Design of Amini 2006 using a DaCM
Proof-mass weight	~ 38 mg	~ 20.8 mg	~ 1.6 mg	~ 1.07 mg
In-plane effective structural stiffness	57.3	59.1	154.6	320.6
First In-plane modal frequency (FE Simulated)	195 Hz	270 Hz	1556 Hz	1947 Hz
Static displacement sensitivity (FE Simulated)	6.5	10.51	0.102	0.127
Figure of Merit (FoM)	**10.3**	**30.3**	**9.6**	**19.0**

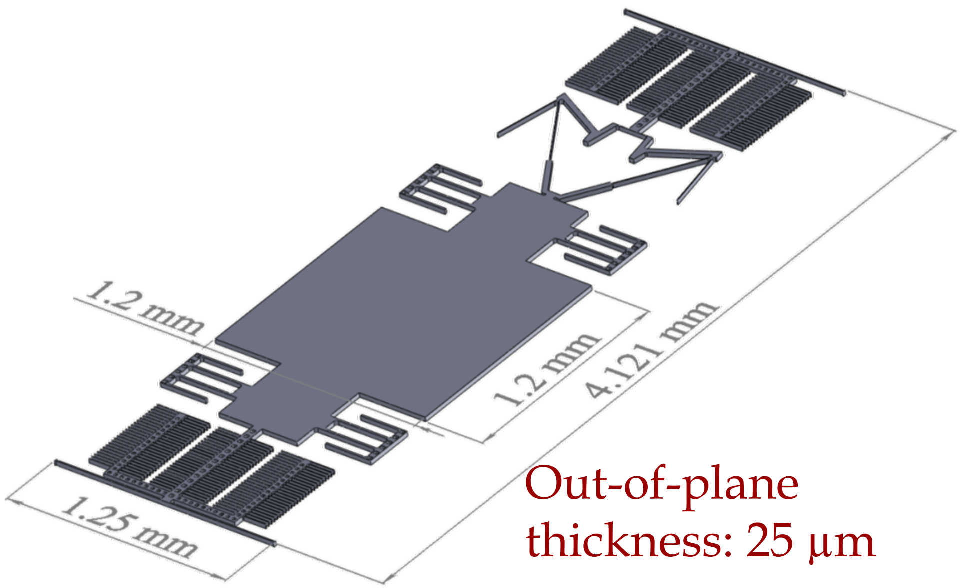
Therefore, we claim:

Sensitivity of any displacement-based sensors such as accelerometers could be improved by designing and incorporating a properly designed DaCM within the same footprint area and without compromising the bandwidth of the device.

Capacitive accelerometers at a Glance

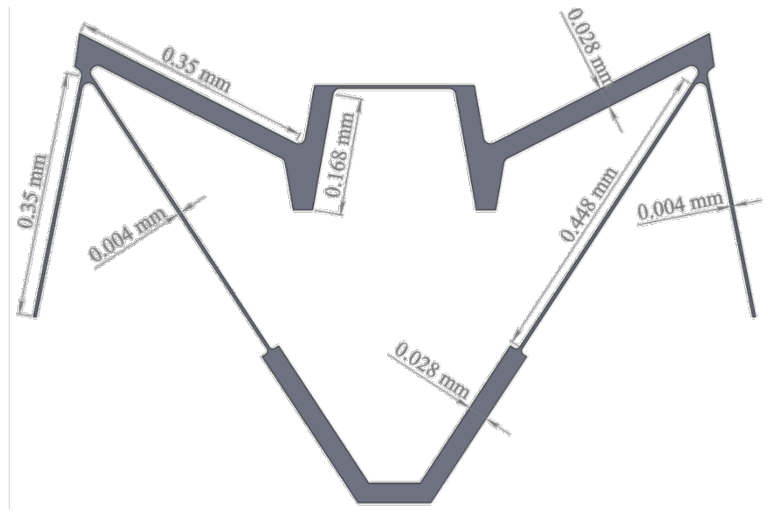
Reference	Overall device size (mm × mm)	Proof-mass size (mm × mm × µm) {Sense gap, µm}	Device Sensitivity		First natural frequency (Hz)	Figure of merit (*FoM*)	Remarks
			$\Delta C / g$ (pF/g) { C_{base} (pF)}	$\Delta V / g$ (V/g) { u / g (µm/g)}			
Experimental results							
Monajemi and Ayazi [16]	5.3 × 3.3	4.4 × 2.2 × 60 {1.3}	4.5 {3.27}	0.25 {0.89}	503	8.9	Single-axis, very small sense-gap
Chae et al. [14]	7 × 9	2.4 × 1 × 500 {1.2}	5.6 {7.7}	0.49 {0.44}	500	4.3	Tri-axial accelerometer with three single-axis accelerometers mounted orthogonally; only in-plane ones are considered here.
The dual-axis device in this work	**8.6 × 8.6**	**3 × 3 × 25 (Single proof-mass for both axes)** {4.0}	**0.29 (both X and Y axes)** {0.98}	**0.58 (both X and Y axes)** {0.59}	**920**	**19.8**	**Dual-axis accelerometer with mechanical amplifiers, circuit gain ~ 2V/pF**
Amini and Ayazi [15]	5 × 6	2 × 6 × 50 {2.3}	0.8 *{11}*	0.8 *{0.10}*	1556	9.6	Single-axis, circuit gain 1 V/pF
Zeimpekis et al. [19]	11.38 × 7.55	4.5 × 4.75 × 50 {10.0}	0.11 {1.57}	2.39 {0.35}	734	7.5	Single-axis and excellent electronics with very high circuit gain ~ 22 V/pF
Abdolvand et al. [18]	7 × 7	(5 × 7 × 100) + (4.7 × 6.7 × 400) {4.3}	35 *{28}*	105 *{6.50}*	200	10.3	Extra seismic mass of 400 µm thick, 100 µm thick structural layer, sense-gap reduction by depositing polysilicon on the sidewalls, circuit gain ~ 3V/pF
Simulated results							
A modified design of [18]; this work	**7 × 7**	**(5 × 3.9 × 100) + (4.7 × 3.6 × 400)** {4.3}	**56** *{28}*	**168** *{10.51}*	**270**	**30.3**	**Assumed circuit gain ~ 3V/pF**
A modified design of [15];	**5 × 6**	**2 × 3.9 × 50** {2.3}	**1** *{11}*	**1** *{0.13}*	**1947**	**19.0**	**Assumed circuit gain ~ 1V/pF**

Single-axis accelerometer Model



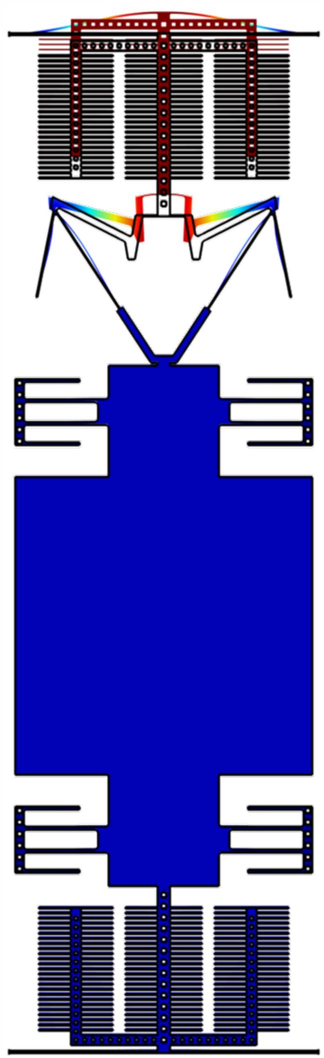
Out-of-plane thickness: 25 µm

3D model of a Single-axis accelerometer with the re-designed and optimized DaCM



Re-designed and optimized non-inverting DaCM

Simulated performance

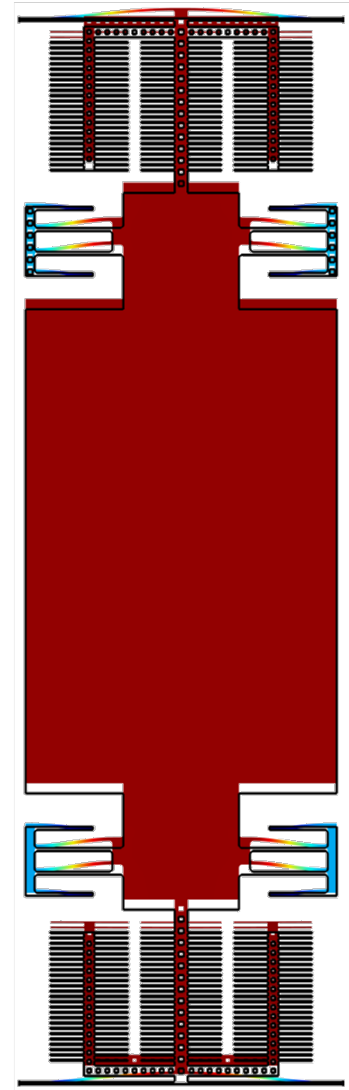


Accelerometer with a DaCM

Performance Comparison	Accelerometer with a DaCM	Accelerometer without a DaCM but same footprint
Displacement sensitivity	~ 8.7 nm/g	~ 1.37 nm/g
First in-plane modal frequency	~ 6.7 kHz	~ 13.6 kHz
Capacitance sensitivity (Change in sense capacitance per unit gravity)	~ 5.8 fF/g with Base capacitance ~ 1.01 pF	~ 0.91 fF/g with Base capacitance ~ 1.01 pF
Maximum stress for 1g body force	~ 0.11 MPa	~ 0.04 MPa
Off-axial sensitivity	~ 1.12 %	~ 5.84 %
Figure of Merit (FoM)	**15.4**	**10.0**

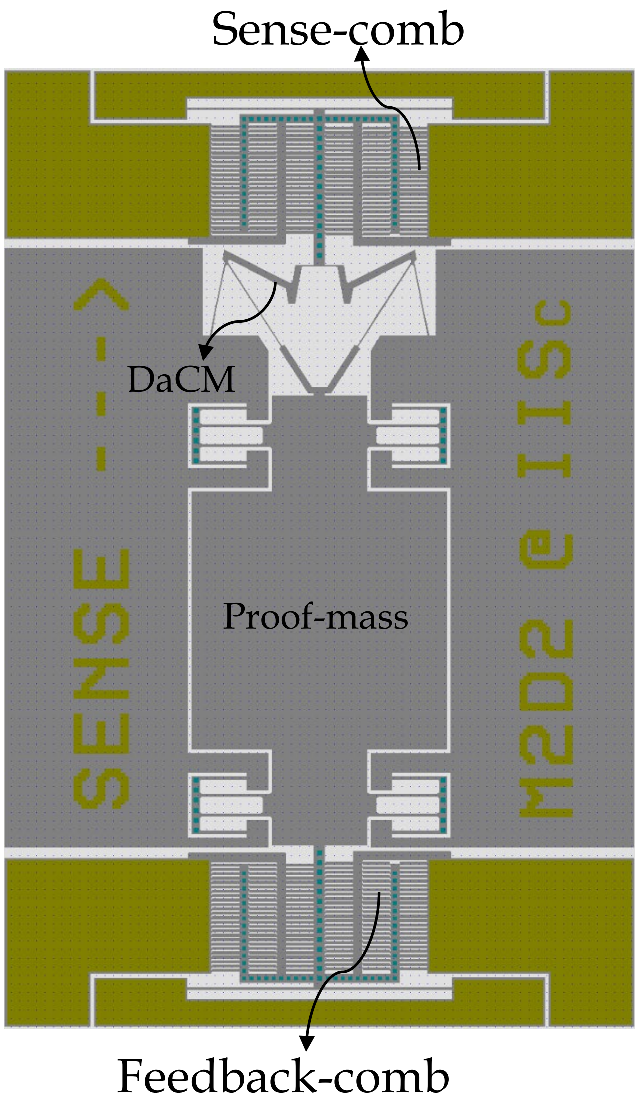
- Simulated Geometric amplification (n) ~ 15.26
- Simulated Net Amplification (NA) ~ (8.7/1.37) ~ 6.35

COMSOL Multiphysics simulation



Accelerometer without a DaCM but with same footprint

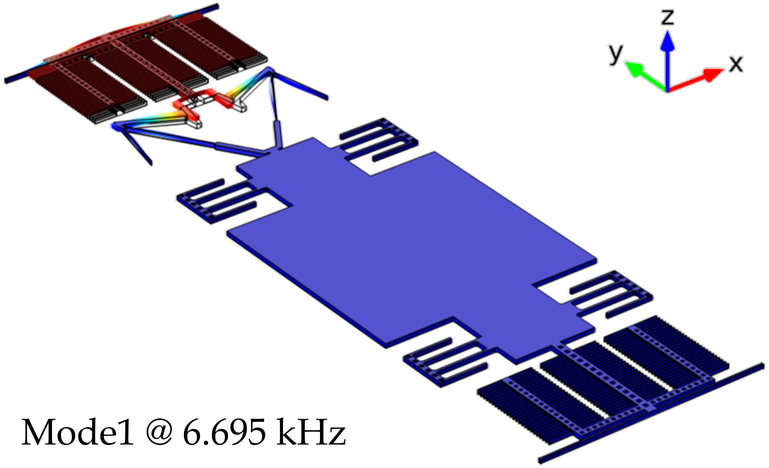
Single-axis capacitive accelerometer with a DaCM



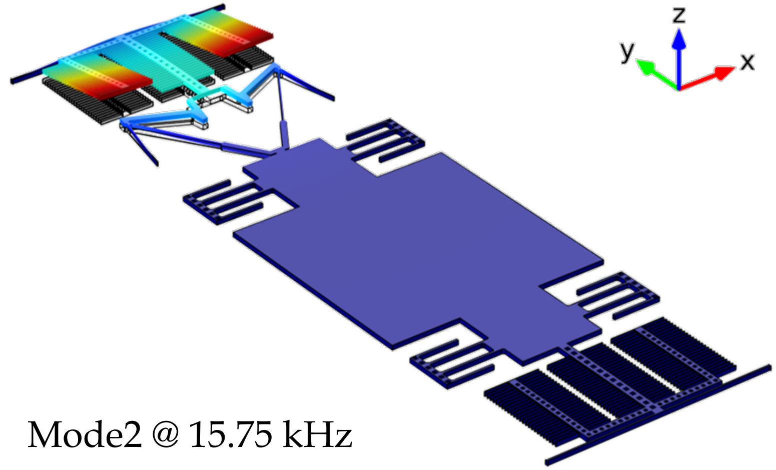
Mask layout

- ❑ DaCM enhances the sensitivity and resolution.
- ❑ Design of the DaCM is modified using topology optimization, shape and size optimization, and intuitive modifications to achieve high NA.
- ❑ DaCM is designed such that the input stiffness of the DaCM matches to the stiffness of the sensor.
- ❑ Design of the DaCM and the external suspension has been optimized to achieve high axial and low cross-axis sensitivity.
- ❑ Selection of optimal design of the DaCM is done using the software "CMDesign" developed by Sudarshan Hegde during his Ph.D thesis.
- ❑ Differential comb arrangements are used to capture the displacement of the proof-mass.
- ❑ Combs at the input side can be used for force feed-back.
- ❑ Total size of the device: 4.25 mm × 1.25 mm
- ❑ Proof-mass weight : 0.12 milli-gram
- ❑ Proof-mass thickness : 25 μm
- ❑ The DaCM, combs and suspensions are of 25 μm thick.
- ❑ Minimum feature size and sense gap : 4 μm and 3 μm

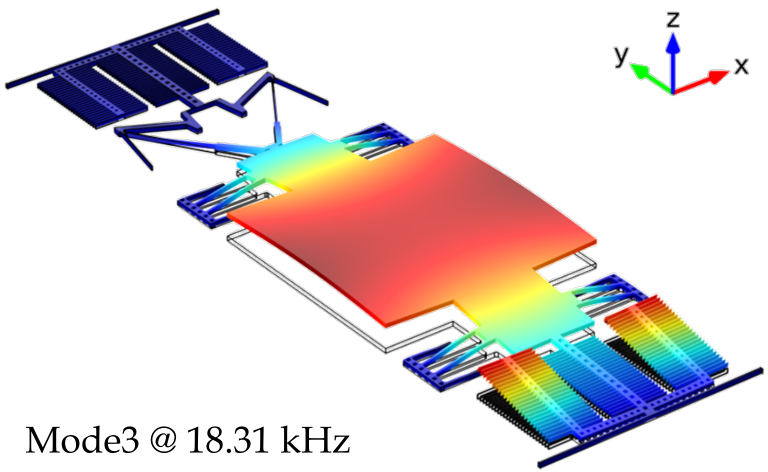
Simulated Modes of vibration



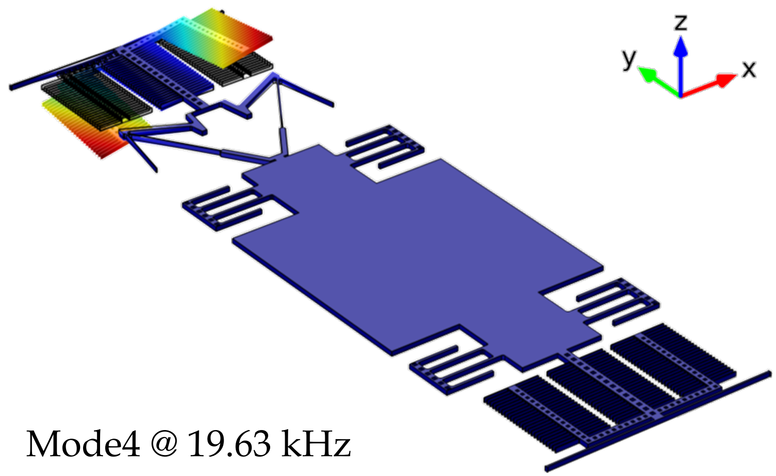
Mode1 @ 6.695 kHz



Mode2 @ 15.75 kHz



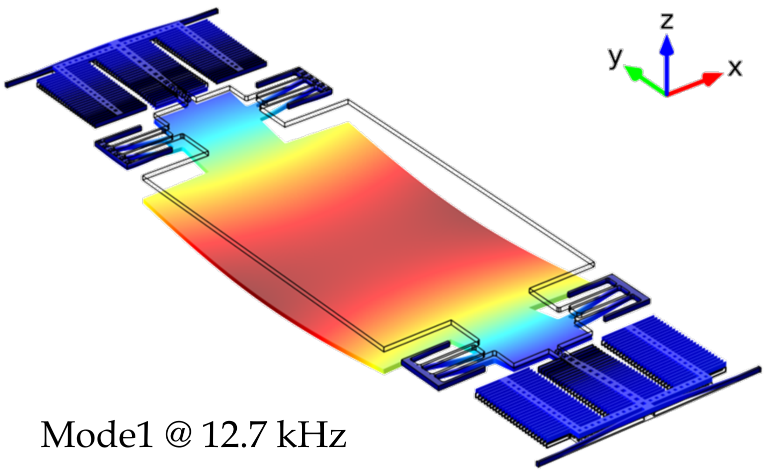
Mode3 @ 18.31 kHz



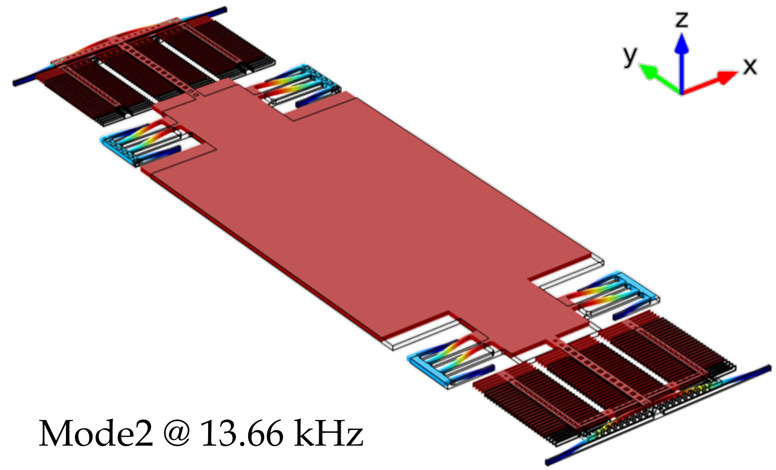
Mode4 @ 19.63 kHz

COMSOL Multiphysics simulation

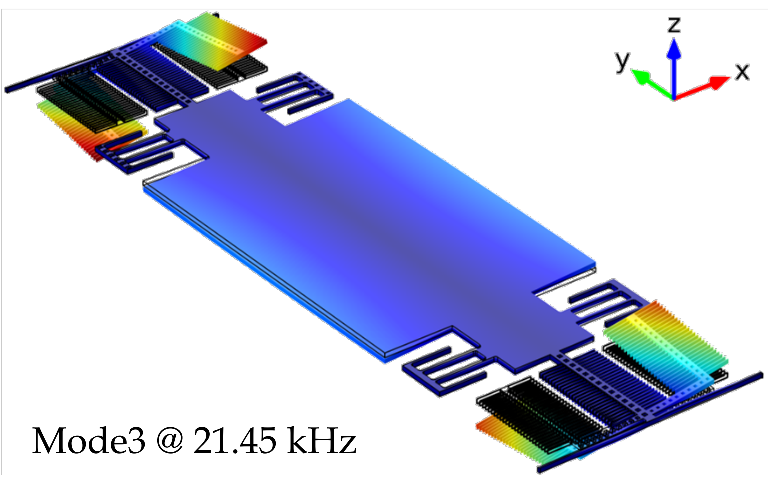
Modes of the accelerometer without a d_aCM but with same footprint



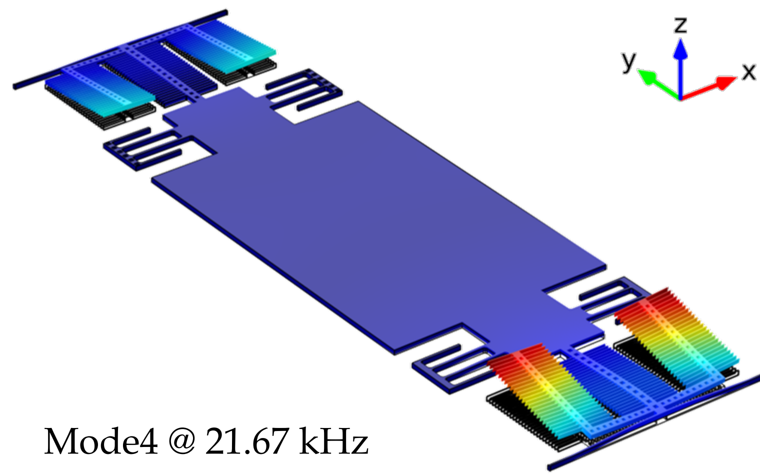
Mode1 @ 12.7 kHz



Mode2 @ 13.66 kHz



Mode3 @ 21.45 kHz



Mode4 @ 21.67 kHz

First mode is an out-of-plane mode. Cross-axial sensitivity along vertical direction will be very high.

Comparison of analytically estimated and simulated lumped parameter values

Specifications	Selection and re-design method	COMSOL Multiphysics
k_{ci} (N/m)	1541	1658.4
k_{co} (N/m)	25.3	33.23
n	13.9	15.26
m_{ci} (kg)	1.49×10^{-8}	1.57×10^{-8}
m_{co} (kg)	6.8×10^{-10}	7.2×10^{-10}
f_0 (kHz)	6.27	6.7
u_{out} per g (m/g)	9.12×10^{-9}	8.7×10^{-9}
NA	6.85	6.35

Microfabrication

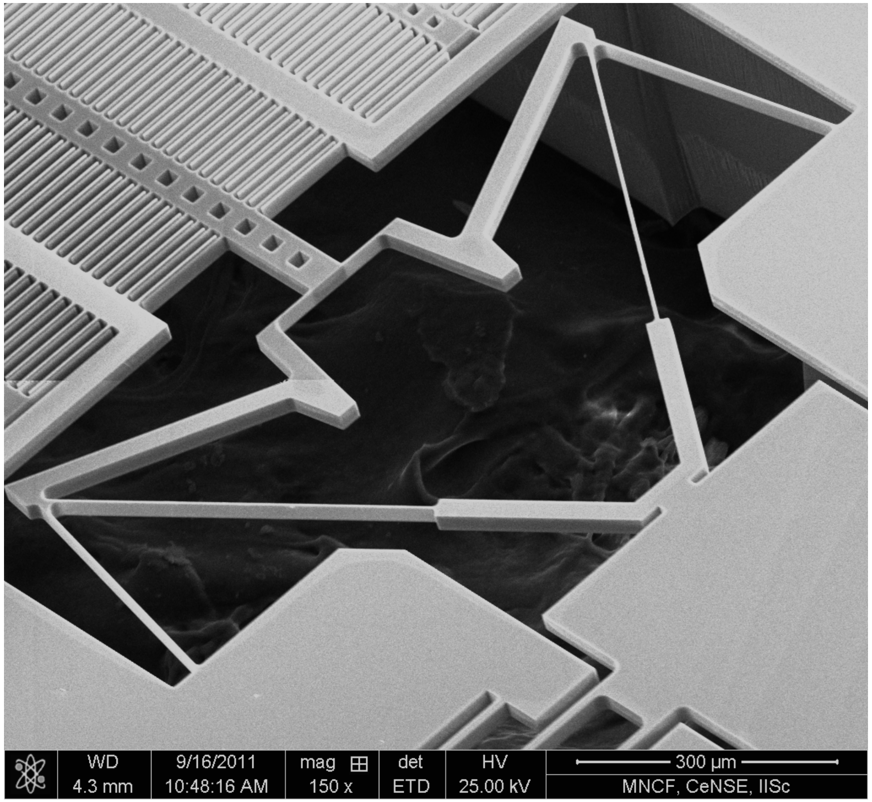
- The design of the milli-g accelerometer using SOIMUMPs (Silion-on-Insulator Multi-User MEMS Processes) have been fabricated in MEMSCAP, USA, a microsystem foundry.

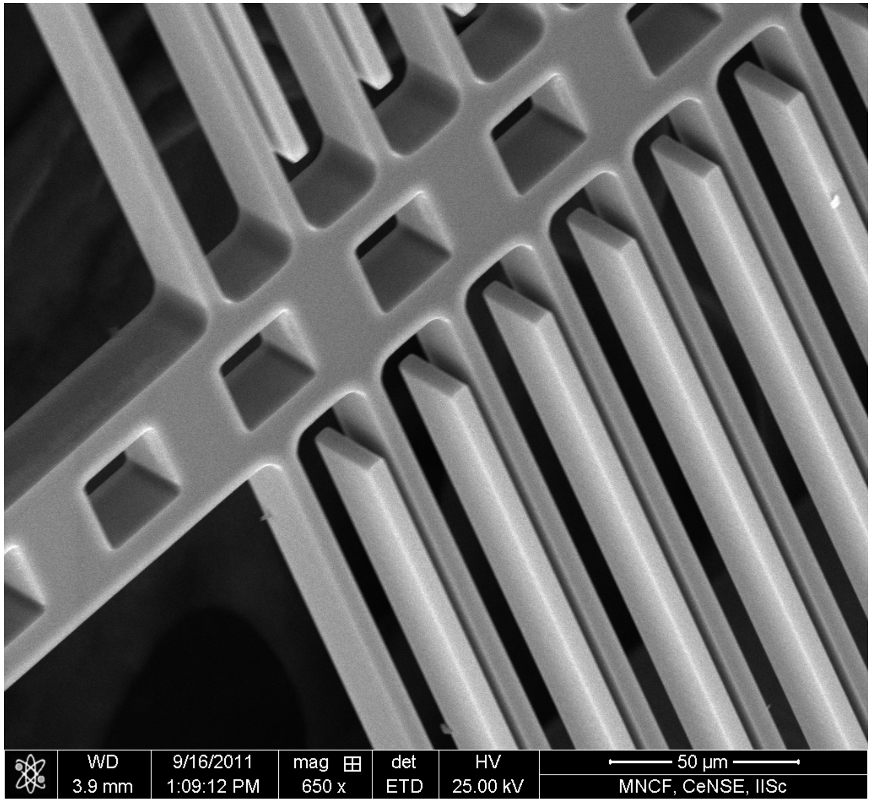
a) A silicon-on-insulator (SOI) wafer is used as the starting substrate:
   - Silicon thickness:10 ± 1 μm or 25 ± 1 μm
   - Oxide thickness:1 ± 0.05 μm (10 μm) or 2 ± 0.05 μm (25 μm)
   - Handle wafer (Substrate) thickness:400 ± 5 μm

b) The Silicon layer is patterned and etched down to the Oxide layer to define the mechanical structures and electrical routing.

c) The Substrate is etched from the "bottom" side to the Oxide layer forming a through hole.

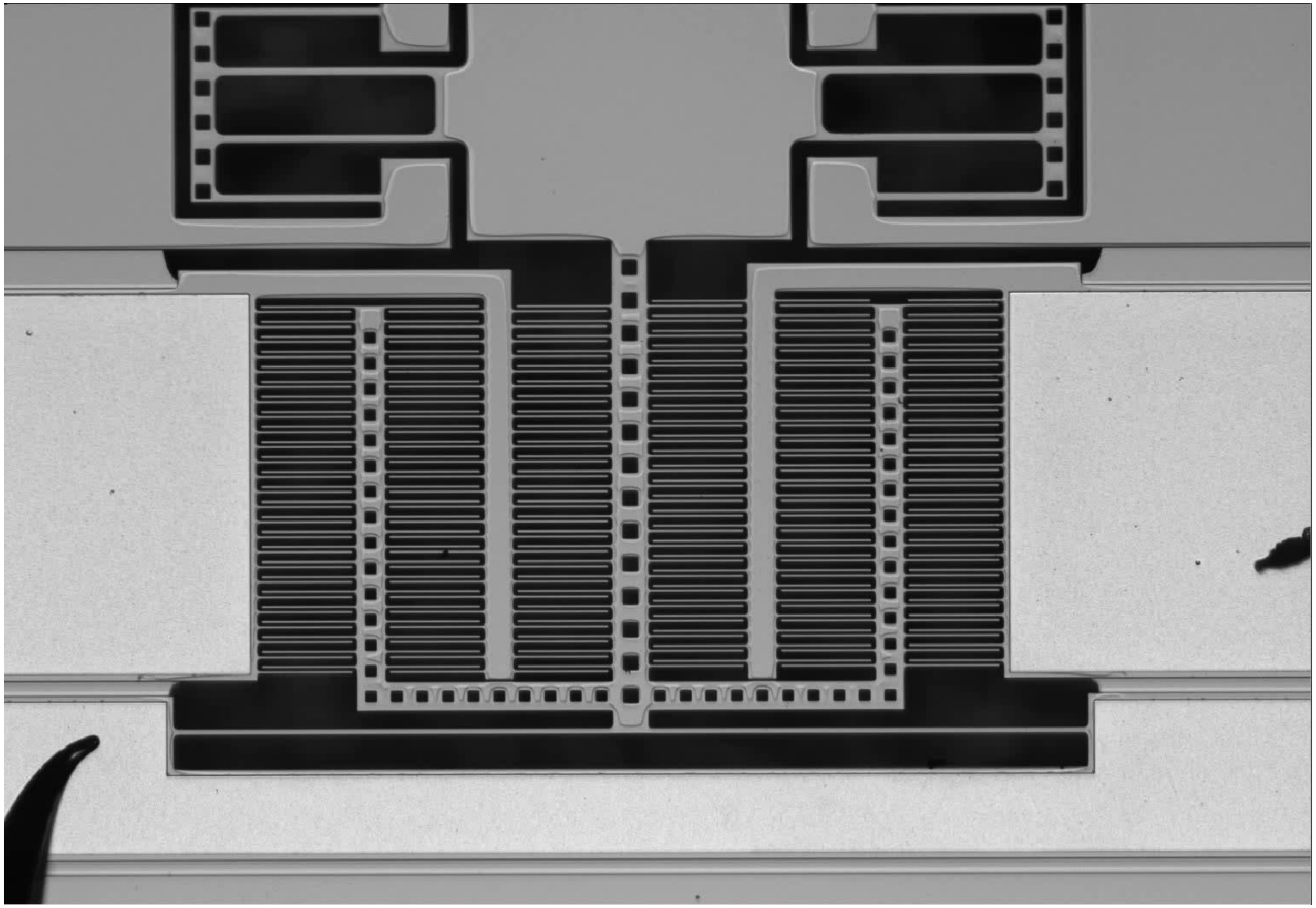
FABRICATED SINGLE-AXIS ACCELEOMETER





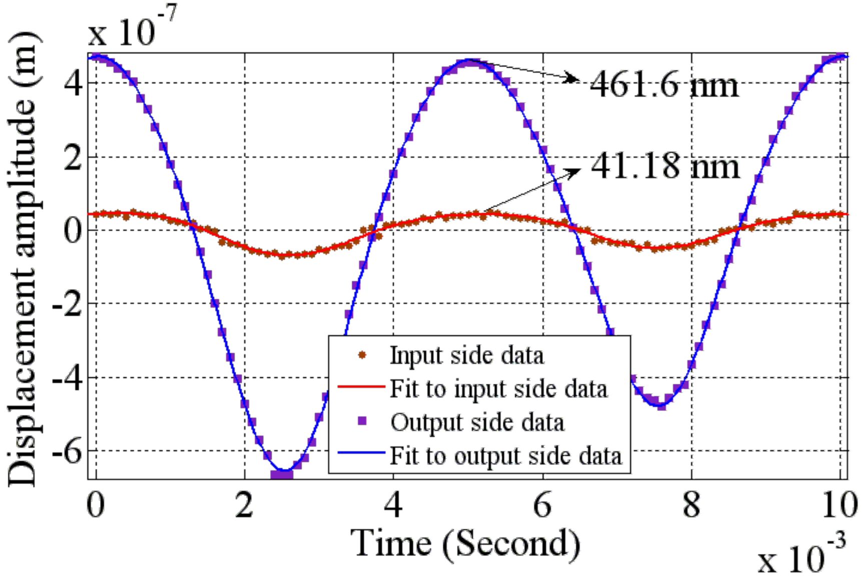
SEM Images

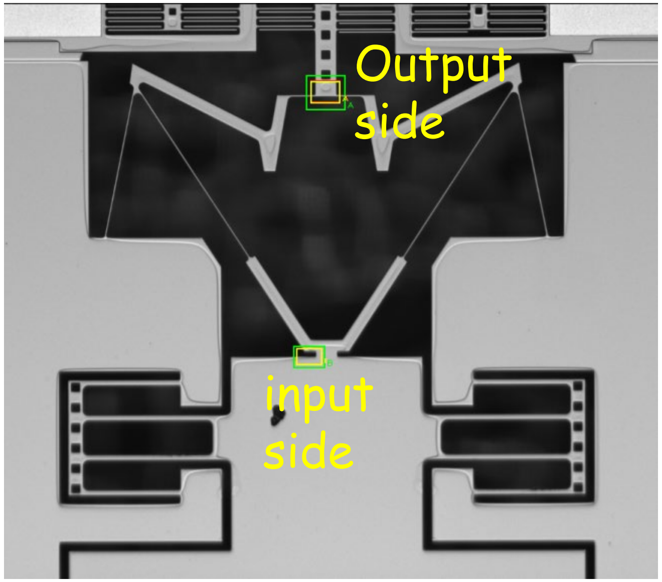
Electrostatic actuation



Amplification observed! How much?

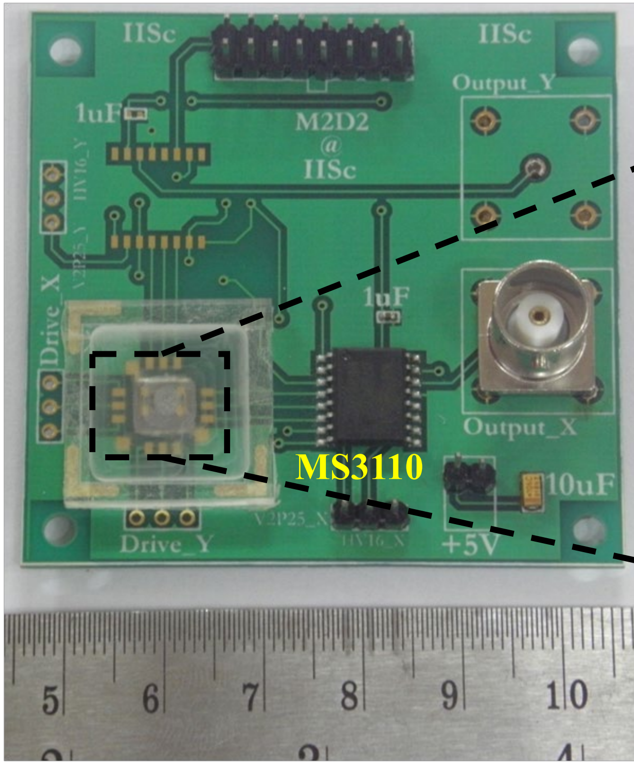
Observed displacement amplification



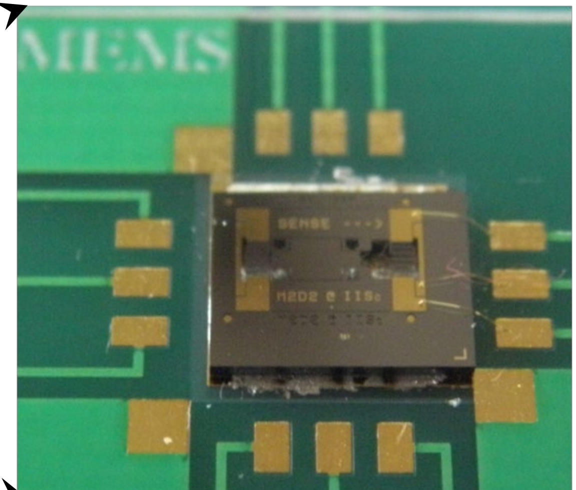


Measured Mechanical Amplification ~ 11

Packaged single-axis accelerometer

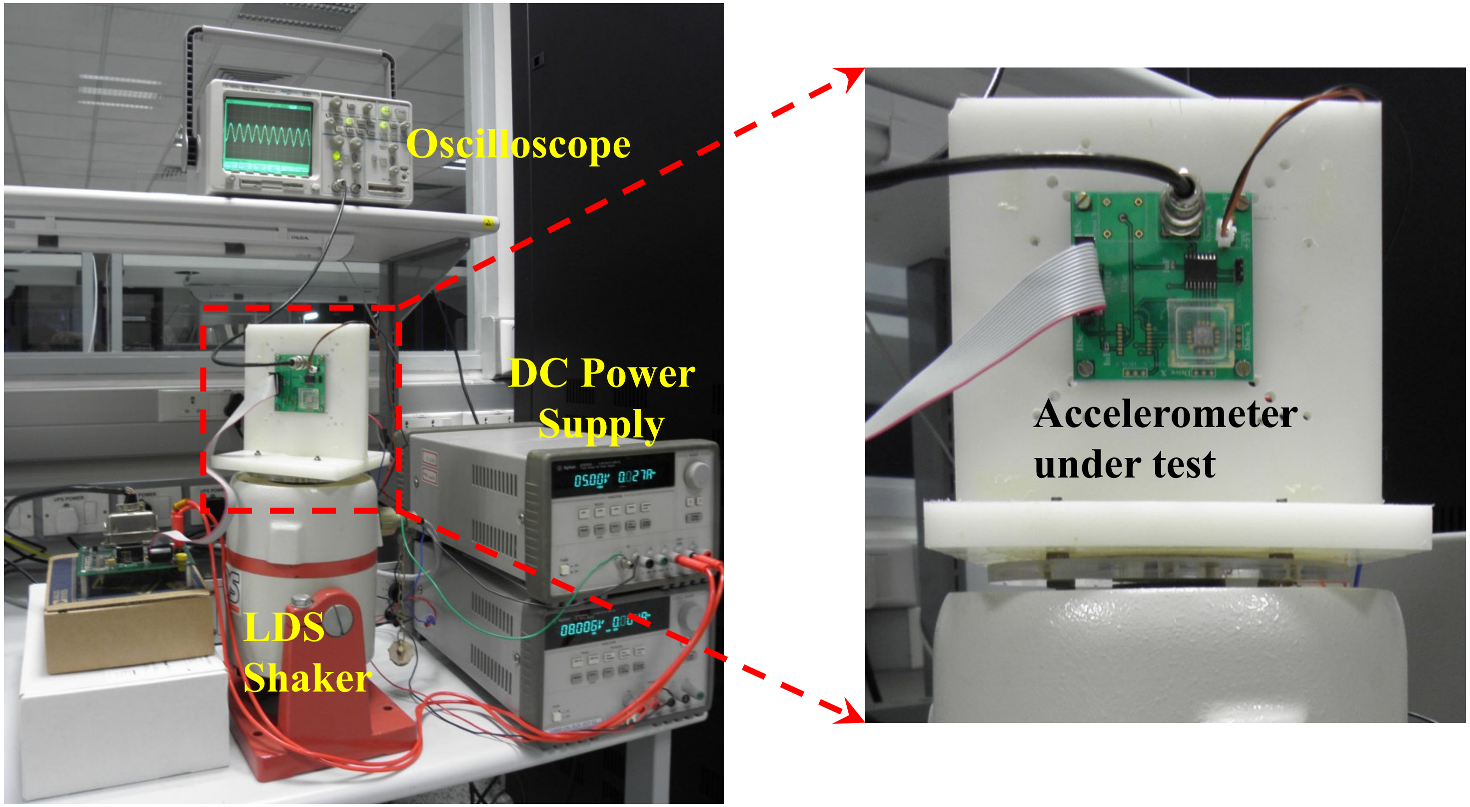


Packaged Single-axis accelerometer on a PCB



Attached and wire-bonded single-axis accelerometer die on a gold-plated PCB.

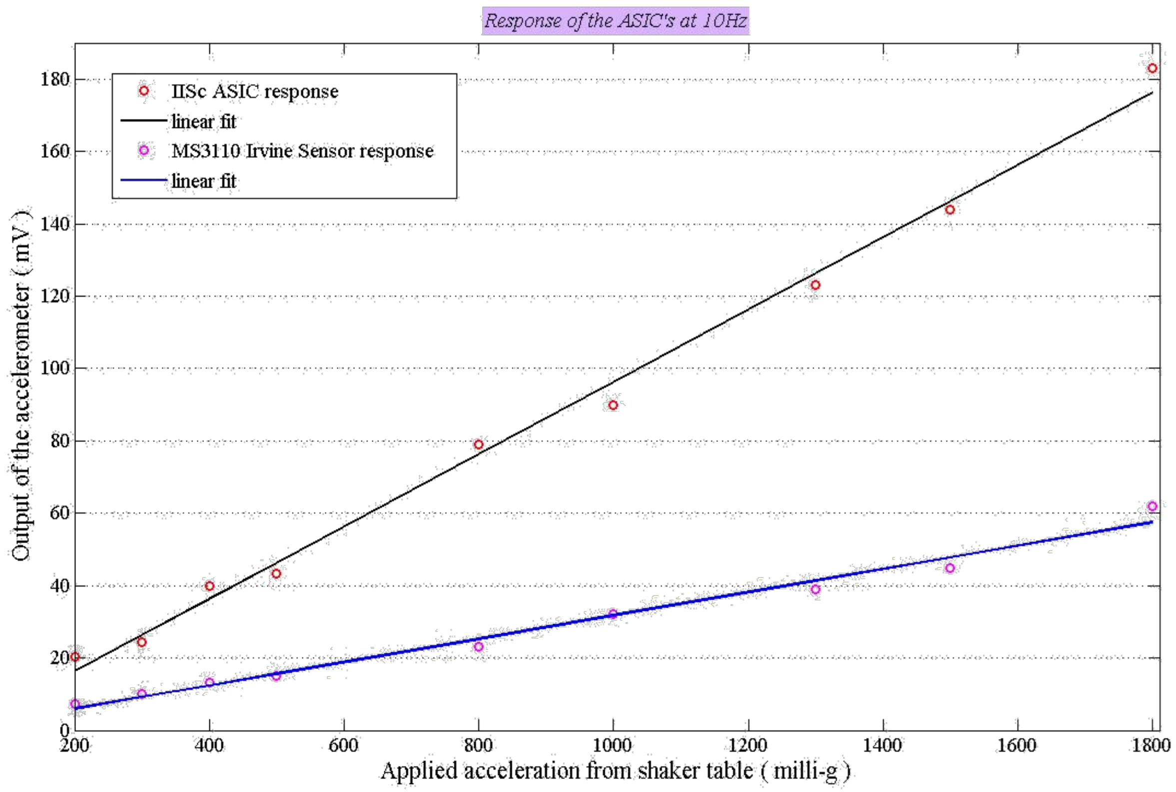
Experimental Setup



The device was operated in Open-loop condition


SINE

Calibration curves of the SOIMUMPs Accelerometer



Best achieved sensitivity:

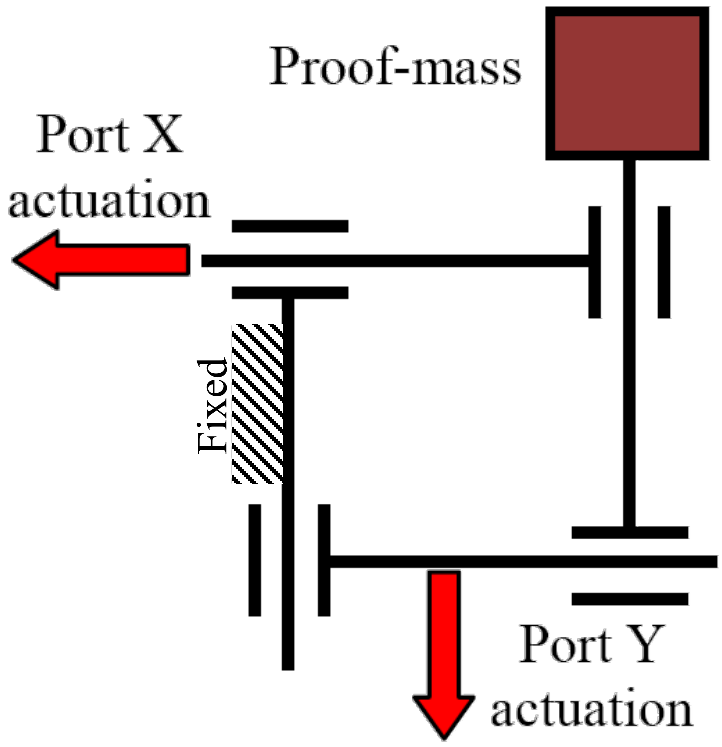
1. Sensor integrated with MS3110: ~ 26.7 mV/g
2. Sensor Integrated with IISc ASIC: ~ 90 mV/g

A DUAL-axis capacitive accelerometer

Publications:

- Khan, S. and Ananthasuresh, G. K., "Improving the Sensitivity and Bandwidth of In-Plane Capacitive Micro-accelerometers using Compliant Mechanical Amplifiers," in *IEEE Journal of Microelectromechanical Systems (JMEMS)*, **DOI: 10.1109/JMEMS.2014.2300231** *(in press)*
- The SmartDetect Project Team, "Wireless Sensor Networks for Human Intruder Detection", in *Journal of the Indian Institute of Science; A Multi-disciplinary Reviews Journal*, Vol. 90, No. 3, 2010, pp. 347-380.
- Khan, S. and Ananthasuresh, G. K., "Performance Enhancement of a Dual-Axis Micro-Accelerometer Using Compliant Displacement-amplifiers," accepted in *IEEE Transducers 2013 and Eurosensors XXVII conference,* Barcelona, Spain, June 2013.
- Khan, S. and Ananthasuresh, G. K., "Sensitivity Enhancement of a Dual-axis In-plane Capacitive Micro-accelerometer using Compliant Displacement-amplifiers," in *5th ISSS National Conference on MEMS, Smart Materials, Structures and Systems*, Sep. 21-22, 2012, Coimbatore, India. (***Recognized with the best Post-graduate Student paper award, 2012***)

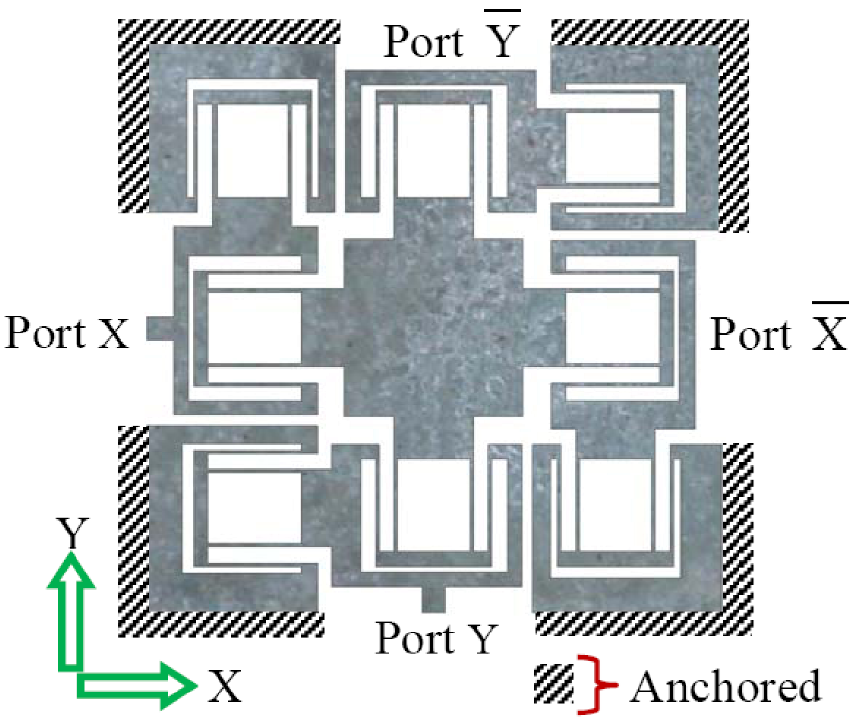
Dual-axis accelerometer: Design



Arrangement of four sliding joints to realize a de-coupling mechanism

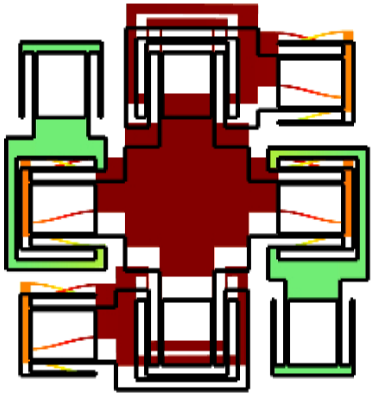
- ❑ Dual-axis accelerometer can measure acceleration in any direction of a plane.
- ❑ Requires two independent motion of actuation.
- ❑ Requires a de-coupling mechanism.
- ❑ Four sliding joints can be arranged to provide necessary de-coupling.
- ❑ Arrangement works perfectly if sliding joints offers:
  - ○ ***Zero axial stiffness***
  - ○ ***Infinite off-axial stiffness***
- ❑ But, ideal sliding joints cannot be realized practically.

Dual-axis accelerometer: Design



- ❑ Design shows a compliant equivalent of four sliding joints arrangement.
- ❑ Eight folded-beam suspensions to replace four sliding joints. (PhD Thesis, S. Awatar 2003)
- ❑ Initially developed for compliant XY stage.
- ❑ Design provides good ***stage isolation*** and ***actuator isolation***.
- ❑ The mechanism used for the purpose of sensing in this paper.
- ❑ Stage is used as the proof-mass.
- ❑ Sense-combs, if added to the Ports, disturb the perfect de-coupling.
- ❑ Off-axial sensitivity increases.
- ❑ Rotation with respect to Z-axis at the Ports are to be limited.
- ❑ Additional suspension can do that.

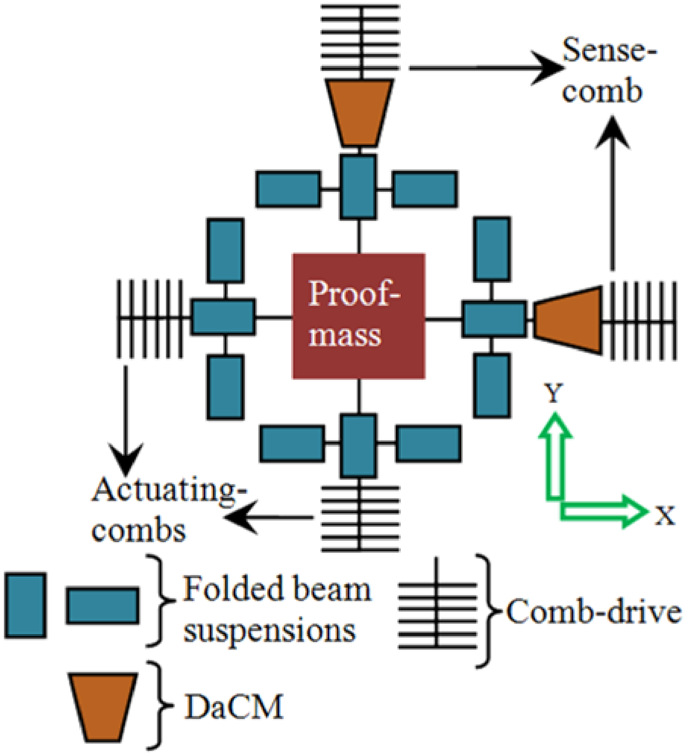
De-coupling

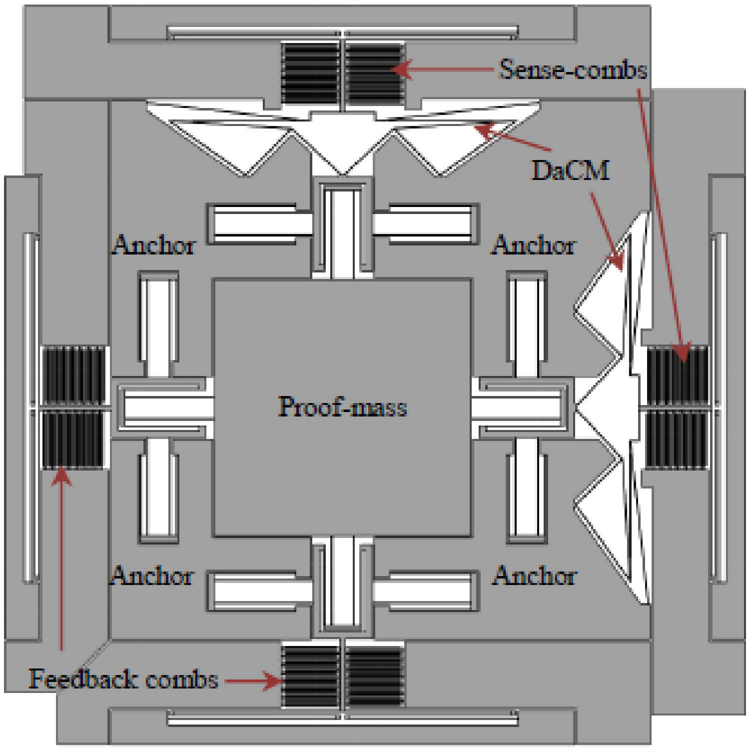


X-axis is not affected when actuated along Y

De-coupling X and Y motions

Dual-axis accelerometer with DaCMs

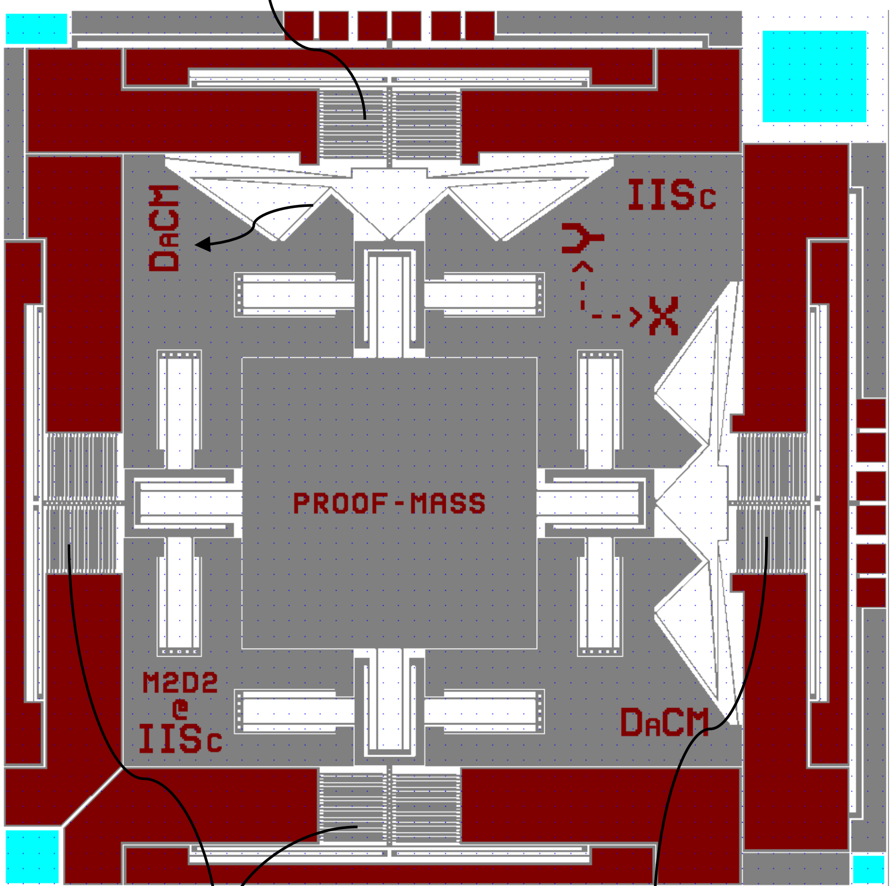




- ❑ A de-coupling mechanism with 12 folded-beam suspensions.
- ❑Higher rotational stiffness.
- ❑ Higher cross-axial stiffness.
- ❑ Low off-axial sensitivity.
- ❑ Two DaCMs were used to amplify axial displacements.

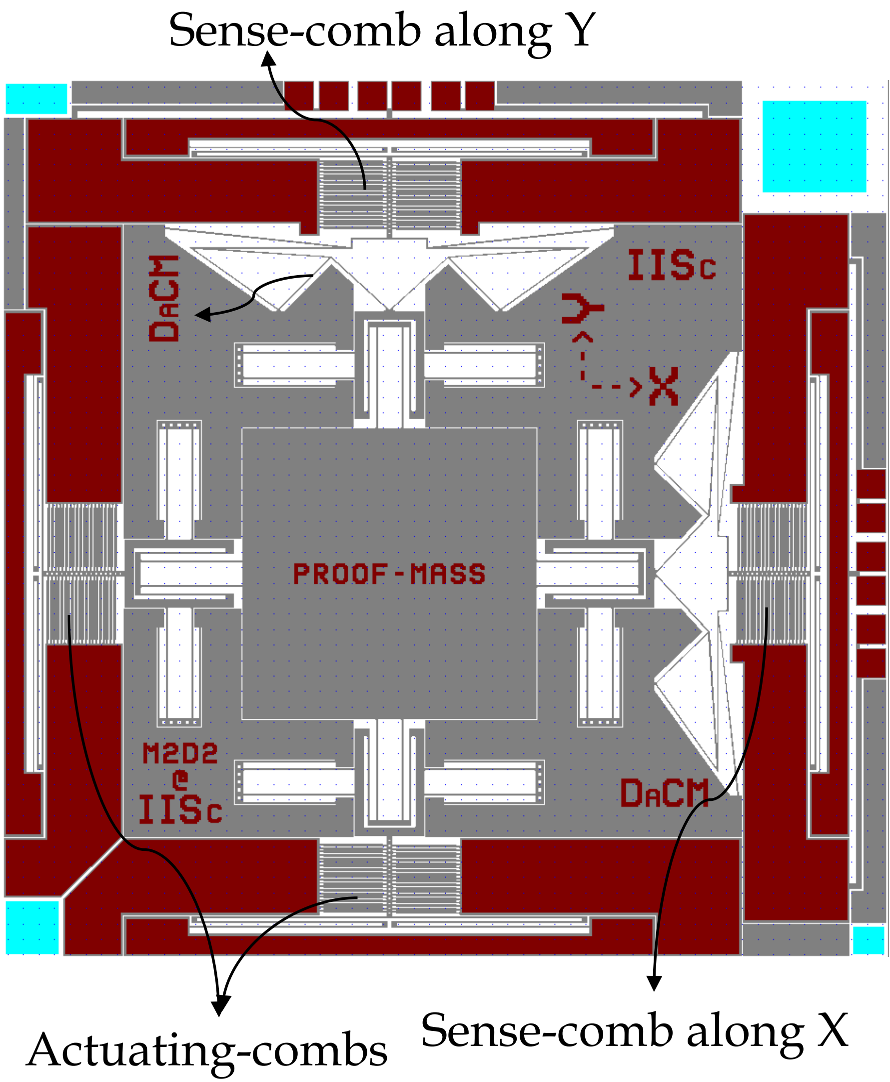
- ❑ Proof-mass moves in the direction of applied acceleration.
- ❑ Actuation of one port does not affect the other orthogonal port.
- ❑ X Ports move only along X by the X component of proof-mass displacement.
- ❑ Similarly for Y.

Dual-Axis Accelerometer with DaCMs



- ❑ An inverting DaCM (M2) is used after necessary re-design and modification.
- ❑ DaCM design is modified using topology optimization, shape and size optimization, and intuitive modifications to achieve high NA.
- ❑ Selection of optimal design of the DaCM is done using the stiffness map-based software "CMDesign" developed by Sudarshan Hegde during his Ph.D thesis.
- ❑ DaCM and the external suspension is optimized to achieve high axial and low cross-axis sensitivity.
- ❑ Differential comb arrangements are used to sense the displacement of the proof-mass.
- ❑ Total size of the device: 8.6 mm × 8.6 mm
- ❑ The Proof-mass size : 3 mm × 3 mm
- ❑ Proof-mass thickness : 25 µm
- ❑ The DaCM, combs and suspensions are of 25 µm thick.
- ❑ Minimum feature size and sense gap : 6 µm and 4 µm

Dual-Axis Accelerometer with DaCMs



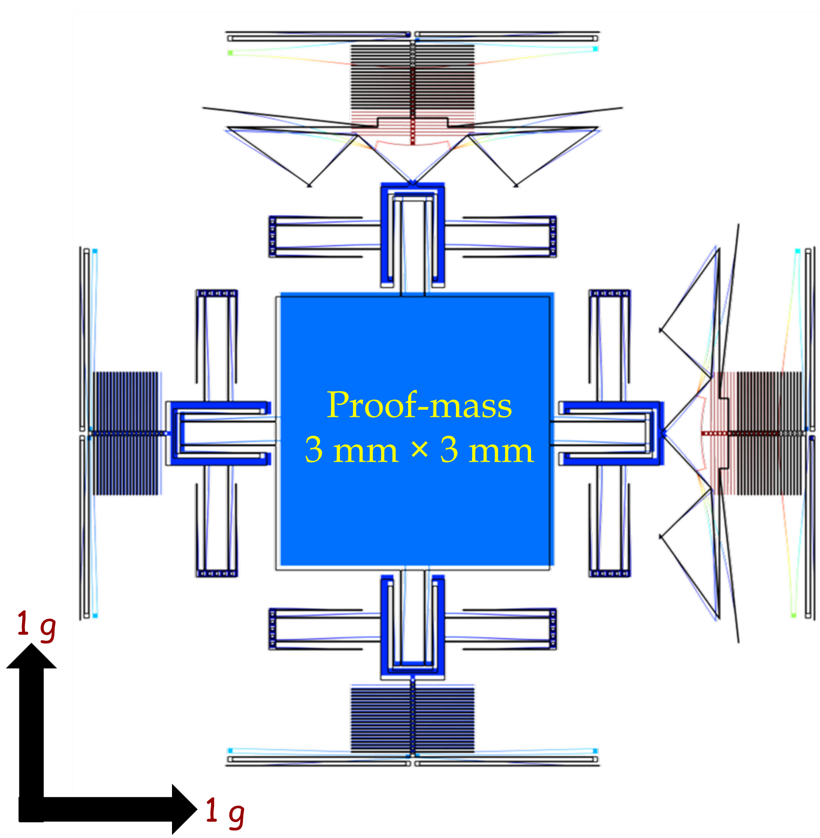
LUMPED PARAMETERS OF THE ACCELEROMETER

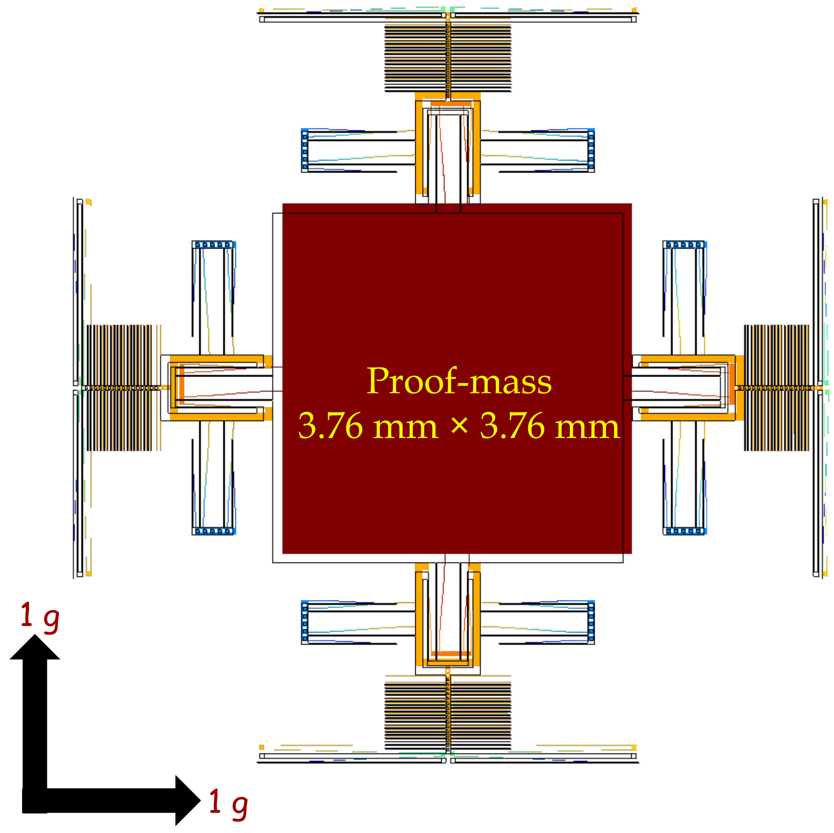
Parameters	Values
Suspension stiffness (k_z) and mass (m_z) of the actuation side	23 N/m and 0.58 × 10⁻⁶ kg
Stiffness of the external suspensions (k_{ext}) and mass of the sense-comb (m_{ext})	0.08 N/m and 0.0155 × 10⁻⁶ kg
k_{ci} and k_{co} values of the DaCM	24.14 N/m and 32.32 N/m
m_{ci} and m_{co} values of the DaCM	4.98 × 10⁻⁸ kg and 5.35 × 10⁻¹⁰ kg
Mechanical Advantage (n) of the DaCM	-6.44

PERFORMANCE SPECIFICATIONS OF THE ACCELEROMETER

Specifications	Analytically estimated	FE Simulated
Static displacement sensitivity	0.594 µm/g	0.586 µm/g
First two in-plane modal frequencies (without damping)	1007.5 Hz (both axes)	1030.56 Hz (both axes)
Net Amplification (NA)	1.56	1.53

Performance analysis and comparison



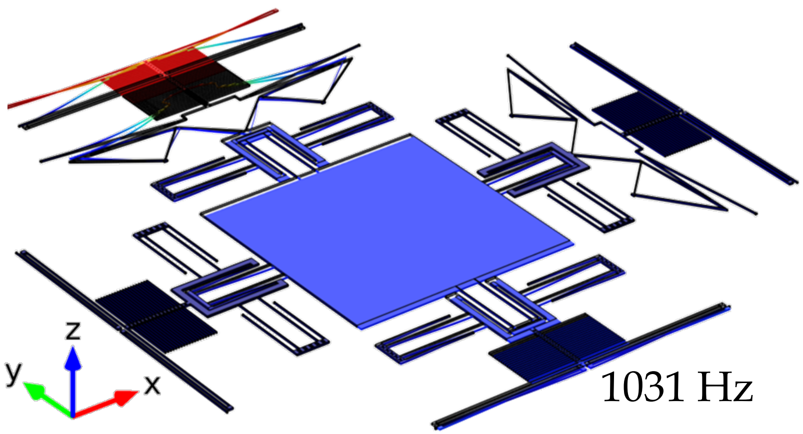


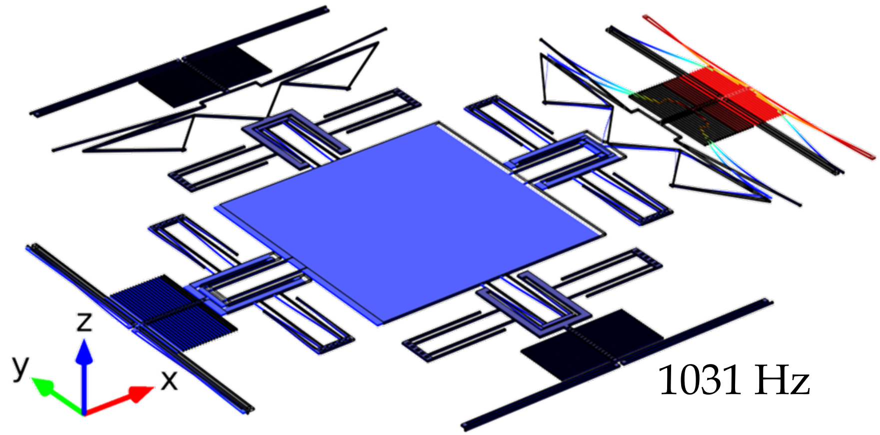
Port Y displacement ~ 0.586 μm
Port X displacement ~ 0.586 μm

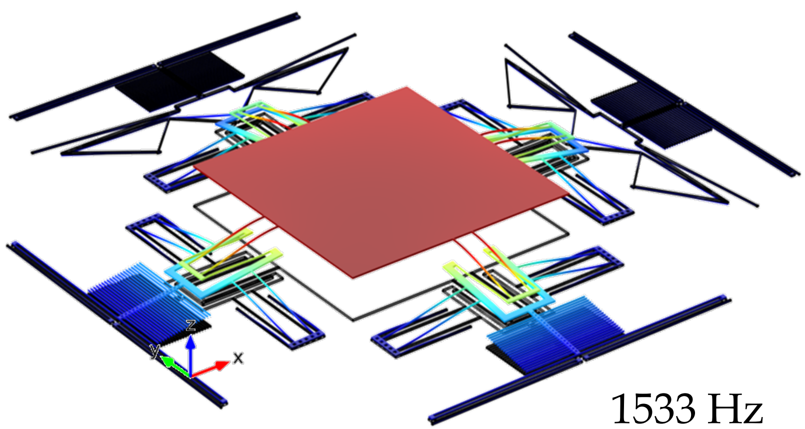
Port Y displacement ~ 0.322 μm
Port X displacement ~ 0.322 μm

All Finite Element simulations were performed in COMSOL, Multiphysics.

Modal analysis







All Finite Element simulations were performed in COMSOL, Multiphysics.

Performance analysis and comparison

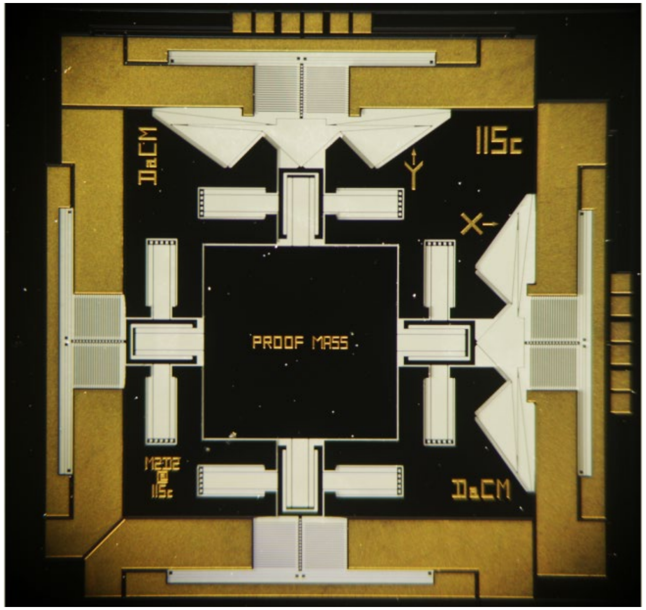
Performance Comparison	Accelerometer with DaCMs	Accelerometer without DaCMs but with same foot-print
Displacement of the sense-comb for 1g body force	~ 0.586 µm	~ 0.322 µm
In-plane first modal frequency	~ 1031 Hz	~ 880 Hz
Capacitance sensitivity	~ 166 fF/g	~ 70 fF/g
Maximum stress for 1g body force	~ 1.2 MPa	~ 1.12 MPa
Off-axial sensitivity	~ 0.662 %	~ 0.18 %
Figure of Merit (FoM)	**24.59**	**9.84**

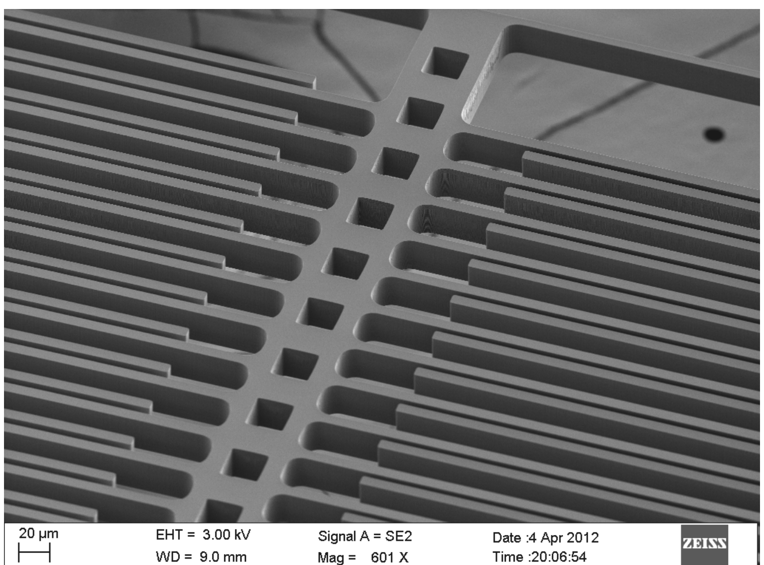
Net Amplification (NA) : 1.53 (53% sensitivity enhancement)

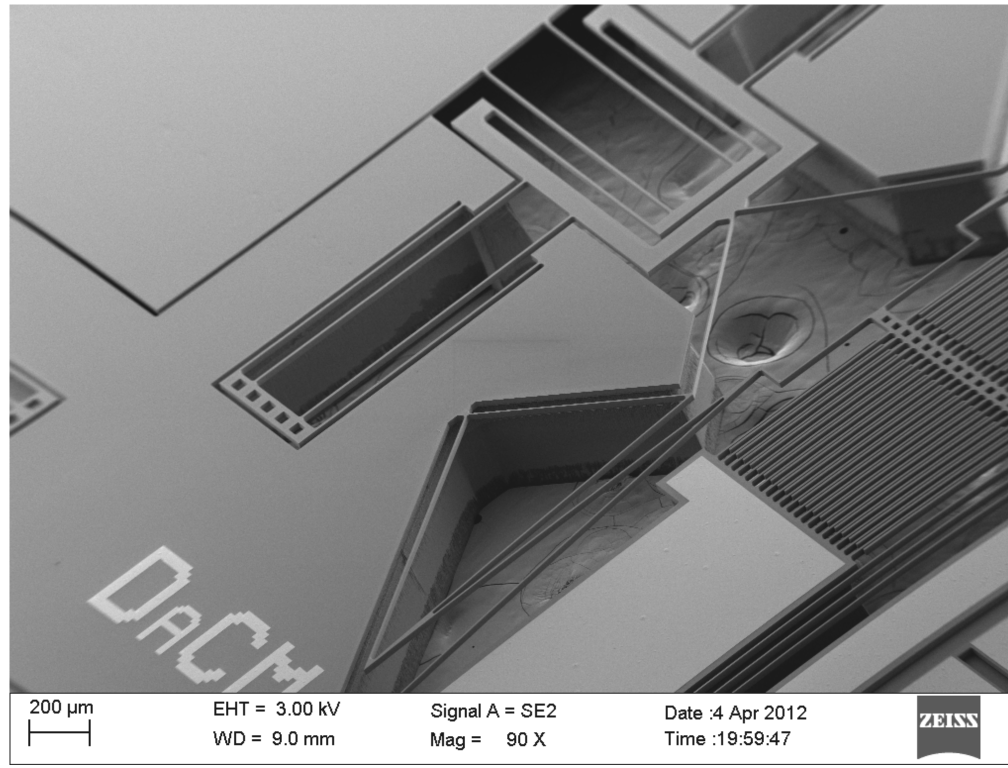
Bandwidth enhancement : 25%

All Finite Element simulations are performed in COMSOL, Multiphysics.

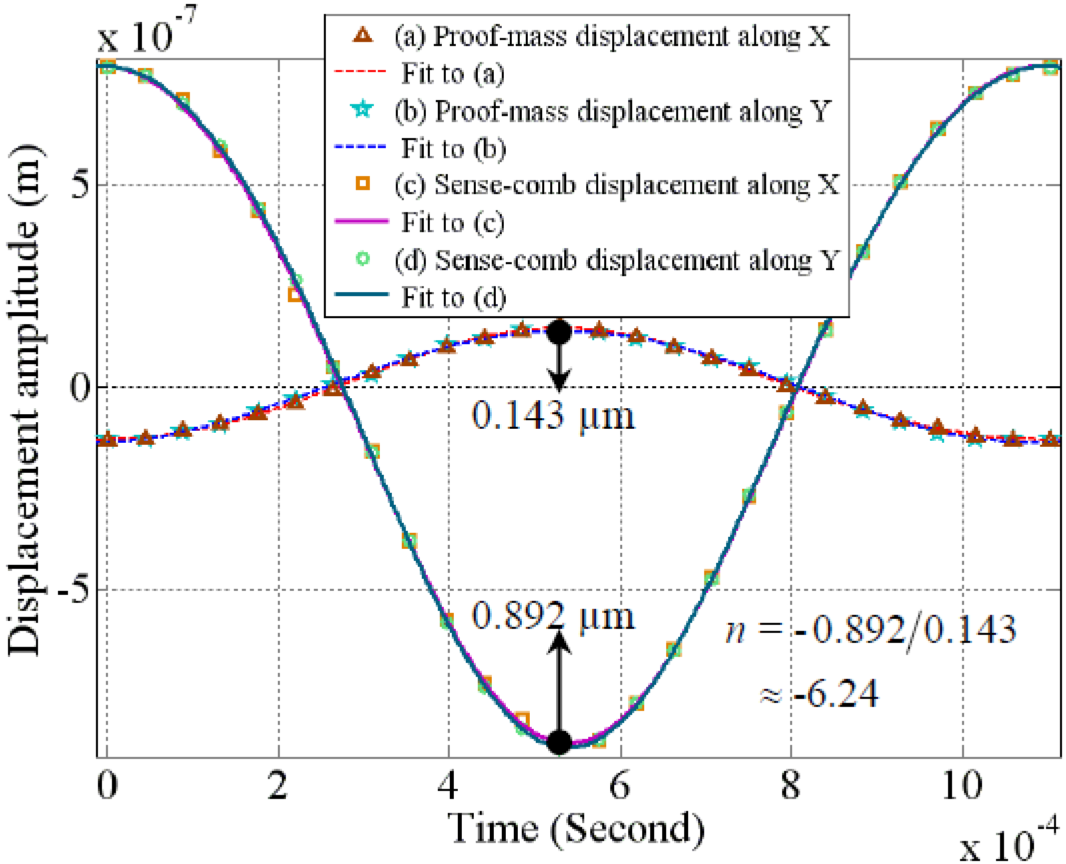
Images of the fabricated device

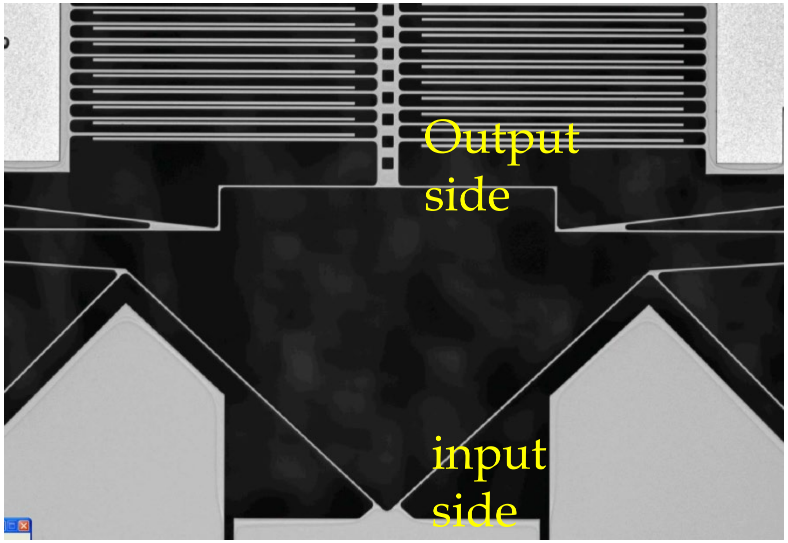




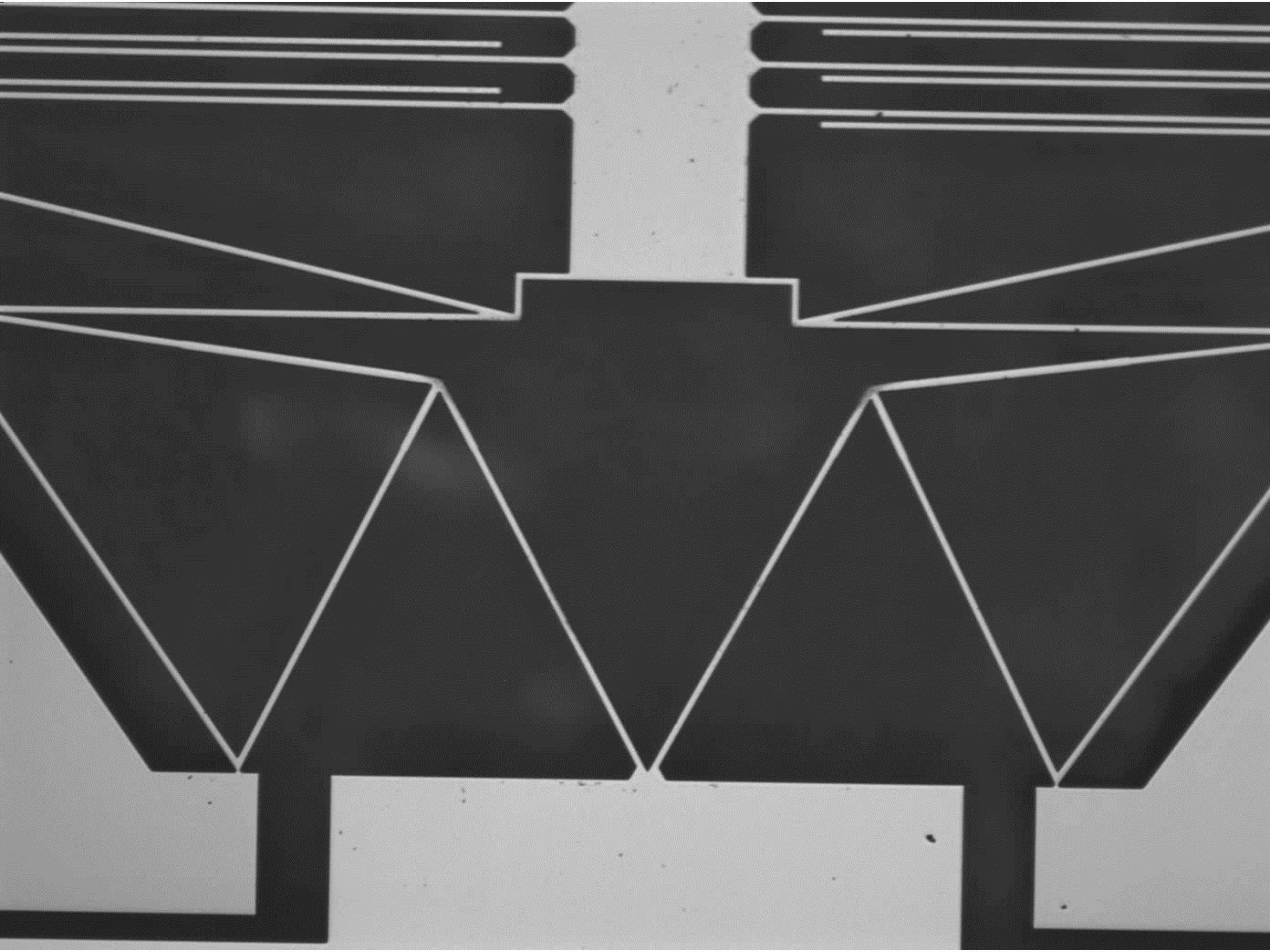


Measured displacement amplification

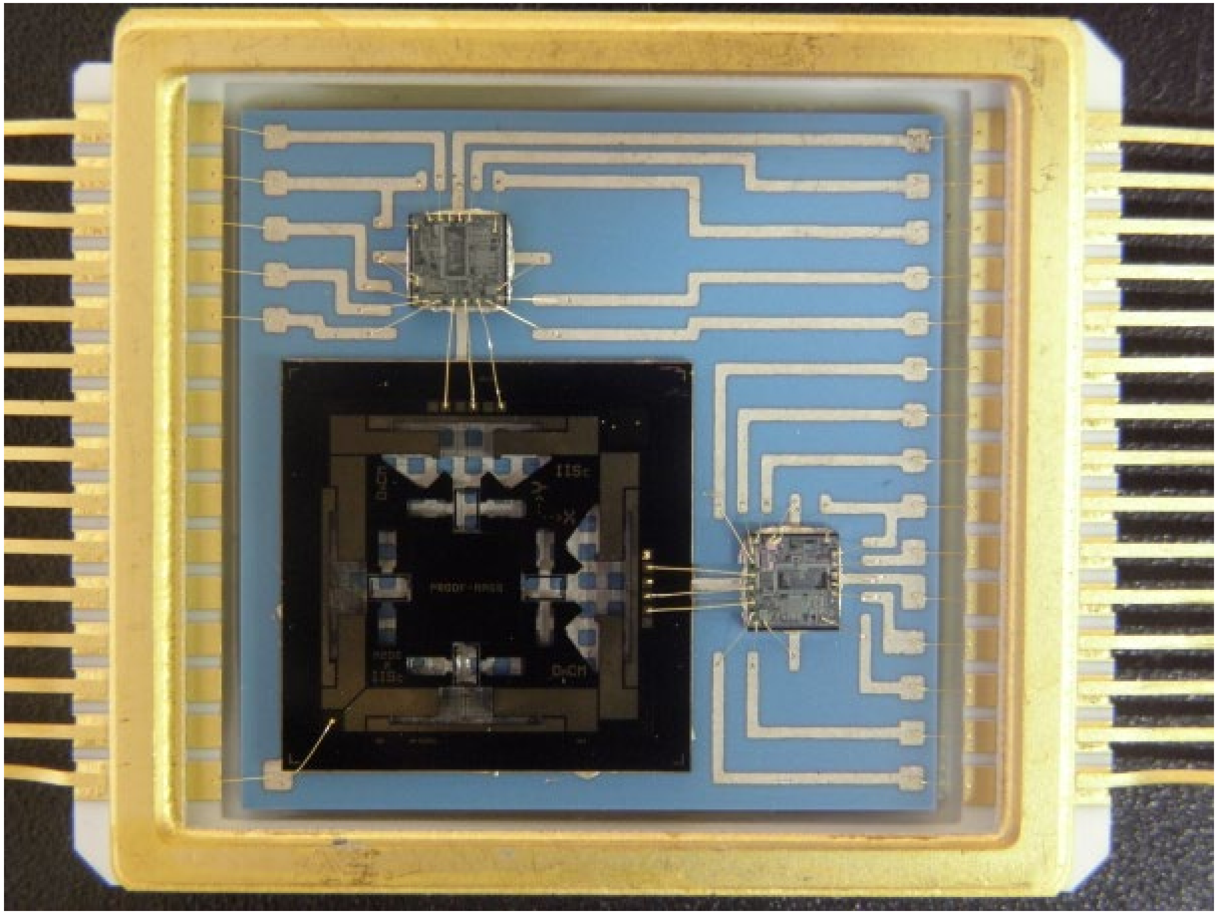




Measured displacement amplification ~ 6.24

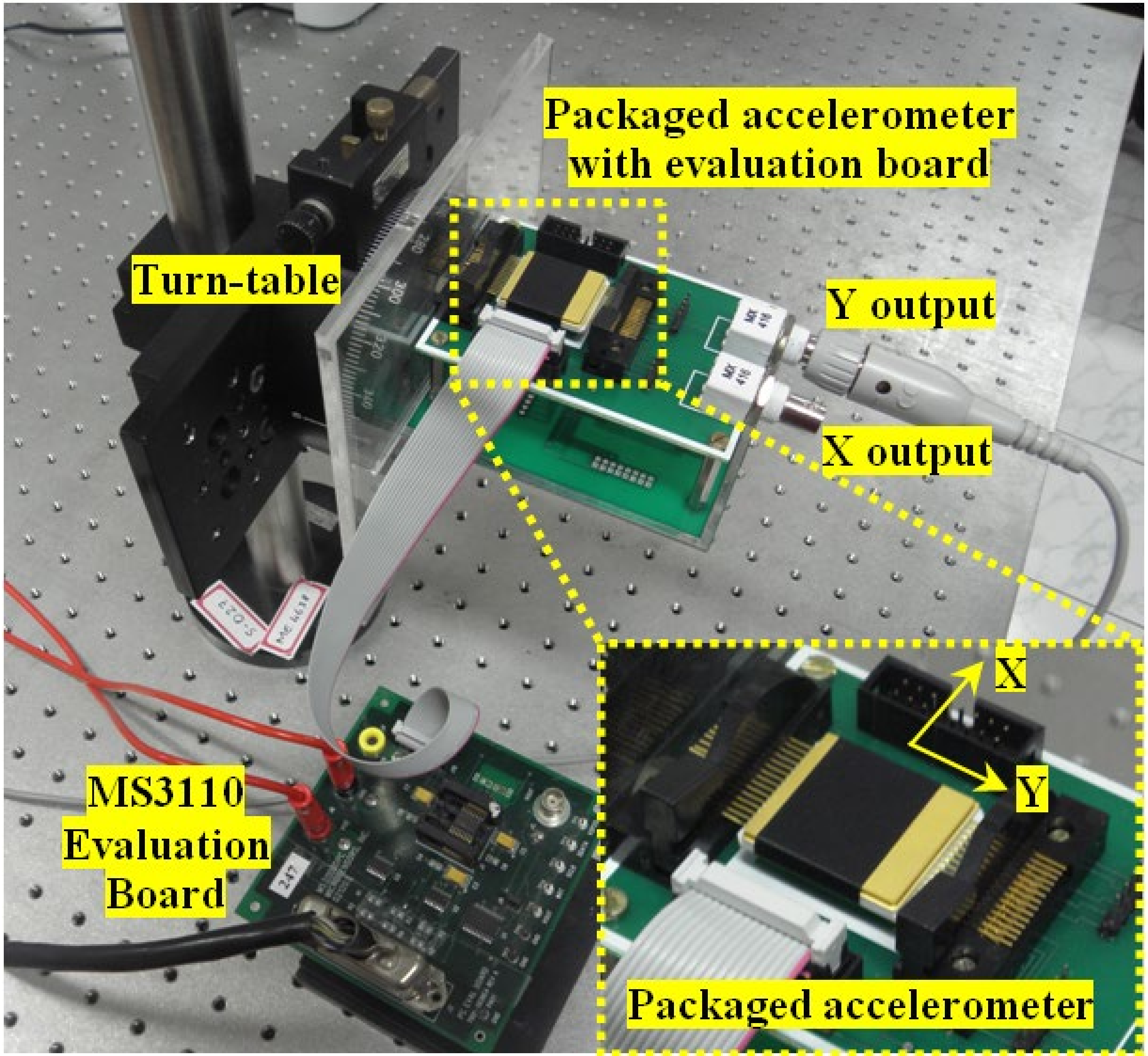


Packaged accelerometer



Packaged dual-axis accelerometer

Experimental setup for static calibration



Main points

- Mechanical amplification enhances sensitivity and resolution without compromising on the bandwidth.
- Displacement-amplification Compliant Mechanisms enhance the performance of capacitive accelerometers.
- Two signals can be separated mechanically.
- Design is an integral part of the development of MEMS.