Leveraging parametric resonance for MEMS vibration energy harvesting

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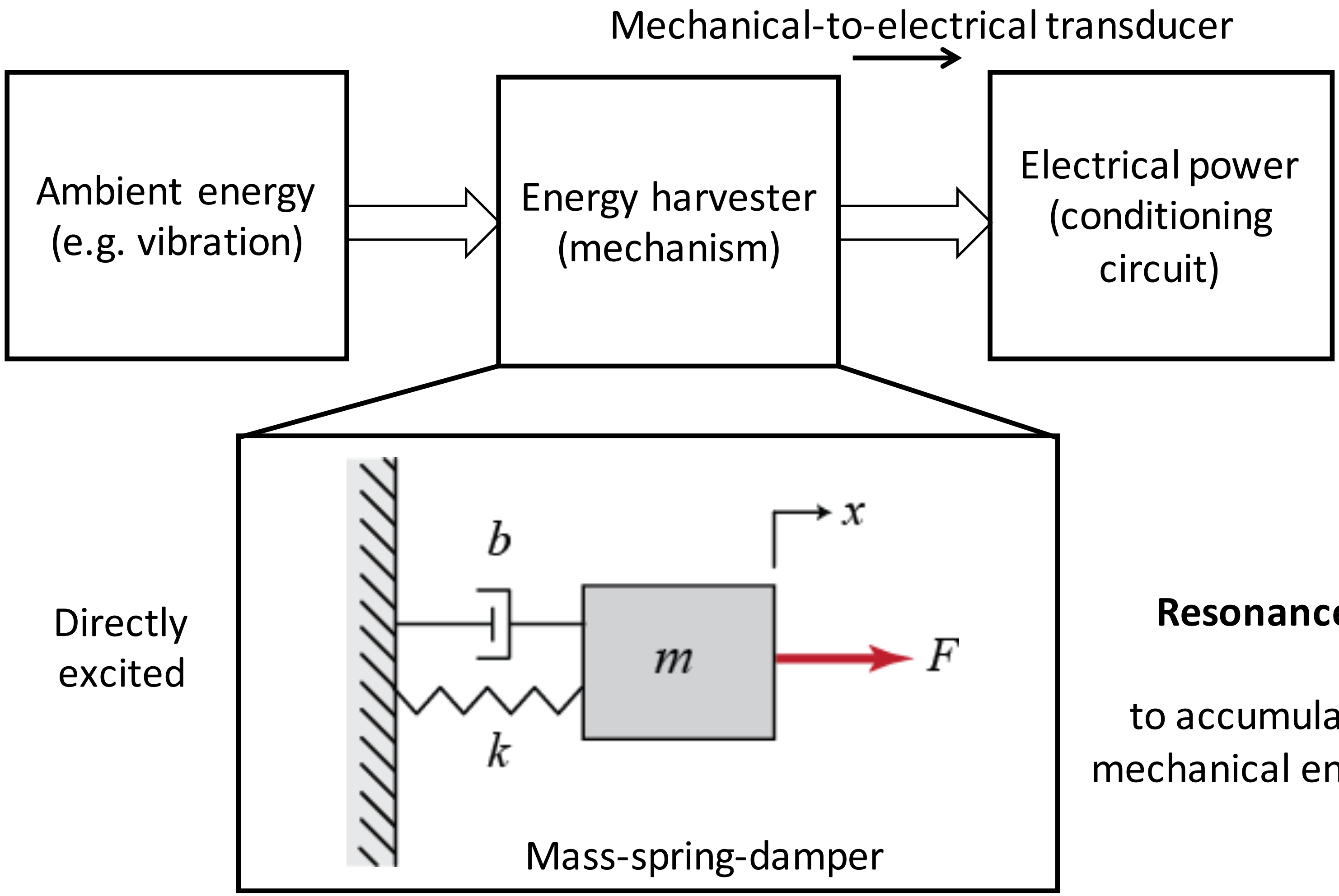
Most resonant vibration energy harvesting



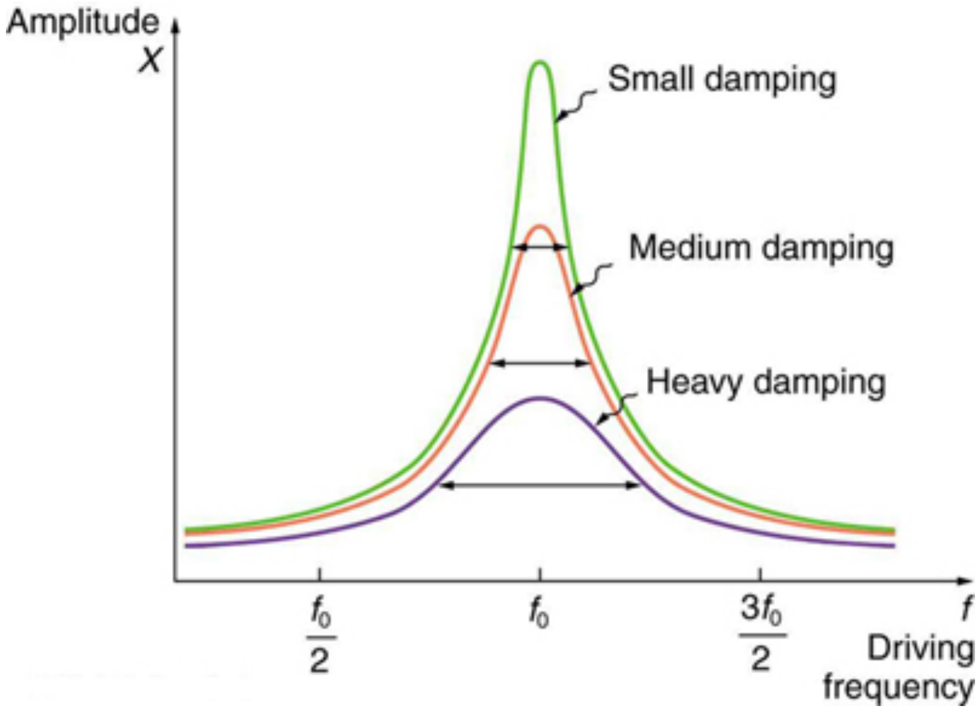
Directly excited

Resonance

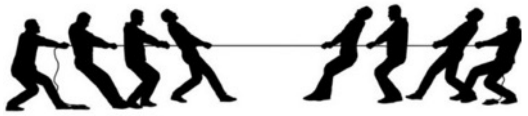
to accumulate mechanical energy

Convention (resonance) and a conundrum

Forcing frequency = resonant frequency = response frequency



A compromise between **frequency bandwidth** and **power amplitude** by adjusting Q



Ideally…

Increase power amplitude…

…while broadening the operational frequency bandwidth…

…for a given drive amplitude and mass

Parametric resonance

Utilises instability phenomenon and can theoretically attain both

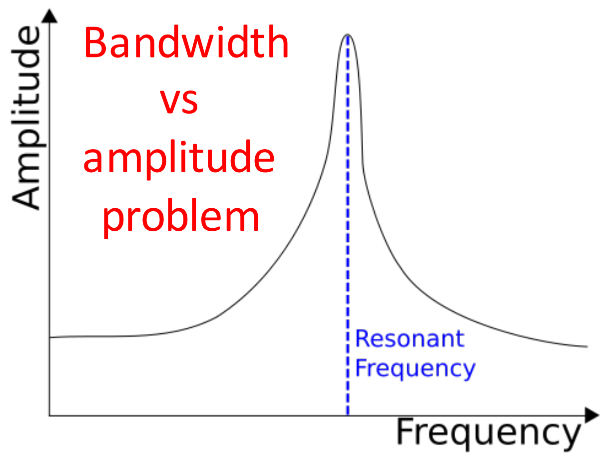
higher amplitude and **broader bandwidth** than direct resonance…

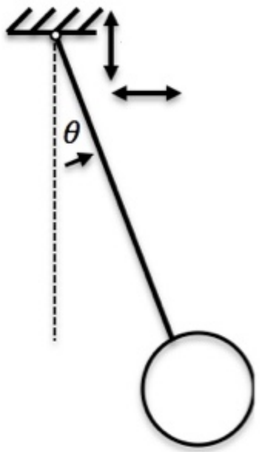
Direct resonance

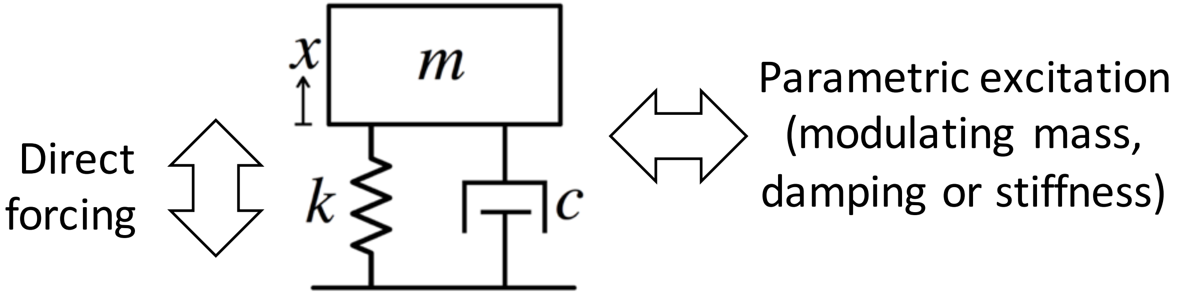
- Directly forced response, typically excitation parallel to displacement
- Excitation frequency at ω_0
- Can tune to maximise **either** power amplitude **or** operational frequency bandwidth

Parametric resonance

- Parametric modulation of at least one of the system parameters
- Excitation frequency at $2\omega_0/n$
- Can tune to increase **both** power amplitude and frequency bandwidth simultaneously







Parametric excitation amplitude

<u>Mathieu equation:</u> $\ddot{x} + c\dot{x} + (\delta + 2\varepsilon\cos(2t))x = 0$

Squared of frequency

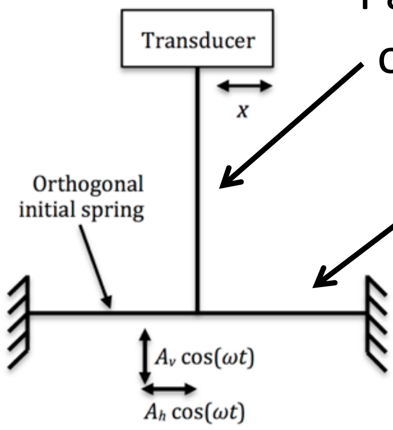
Time domain coefficient

There is a catch…

Initiation threshold amplitude…

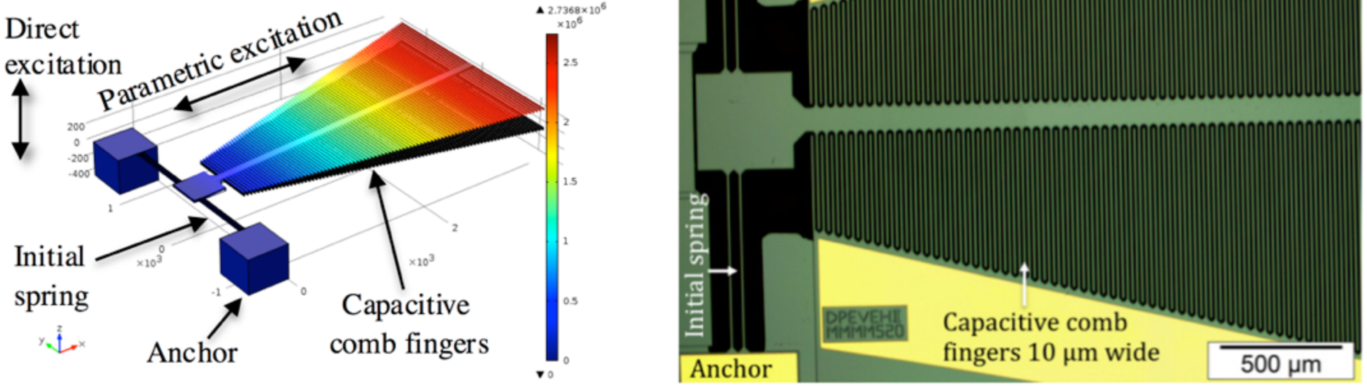
…and precise internal frequency matching.

Autoparametric Resonance in Electrostatic MEMS Vibration Energy Harvester (2011-2013)



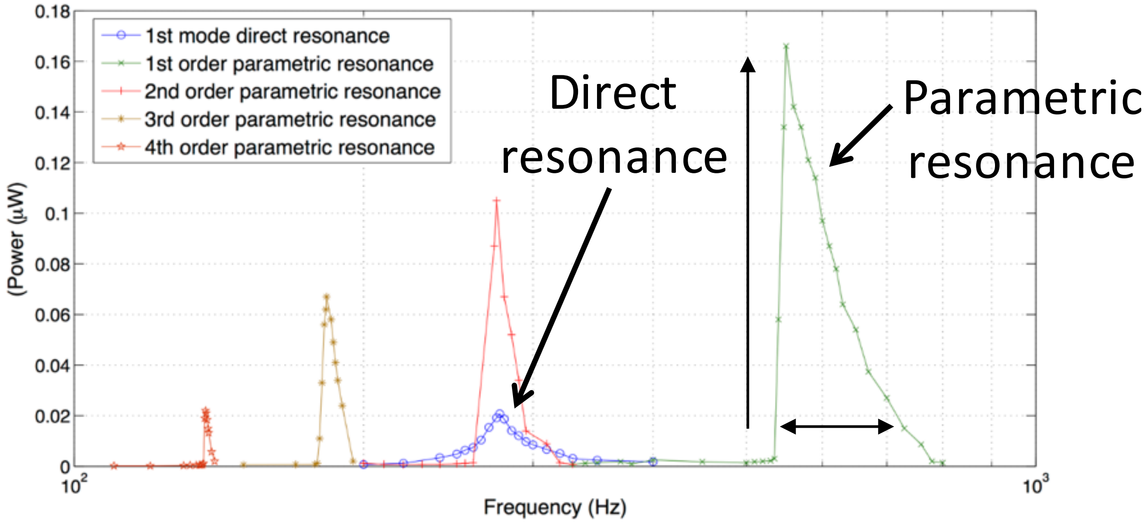
Parametric oscillator

Initial spring design to minimise initiation threshold

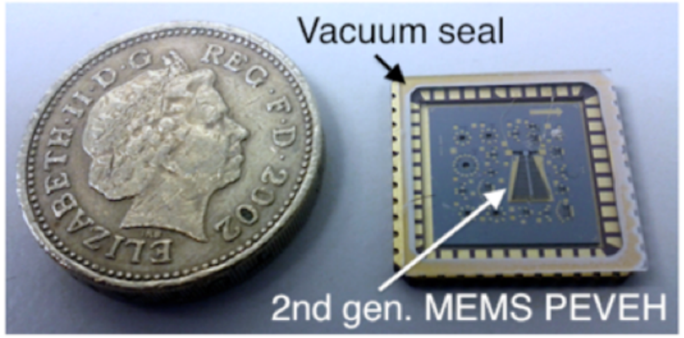


(a) COMSOL Design (b) Optical micrograph

Driven at 0.5 g

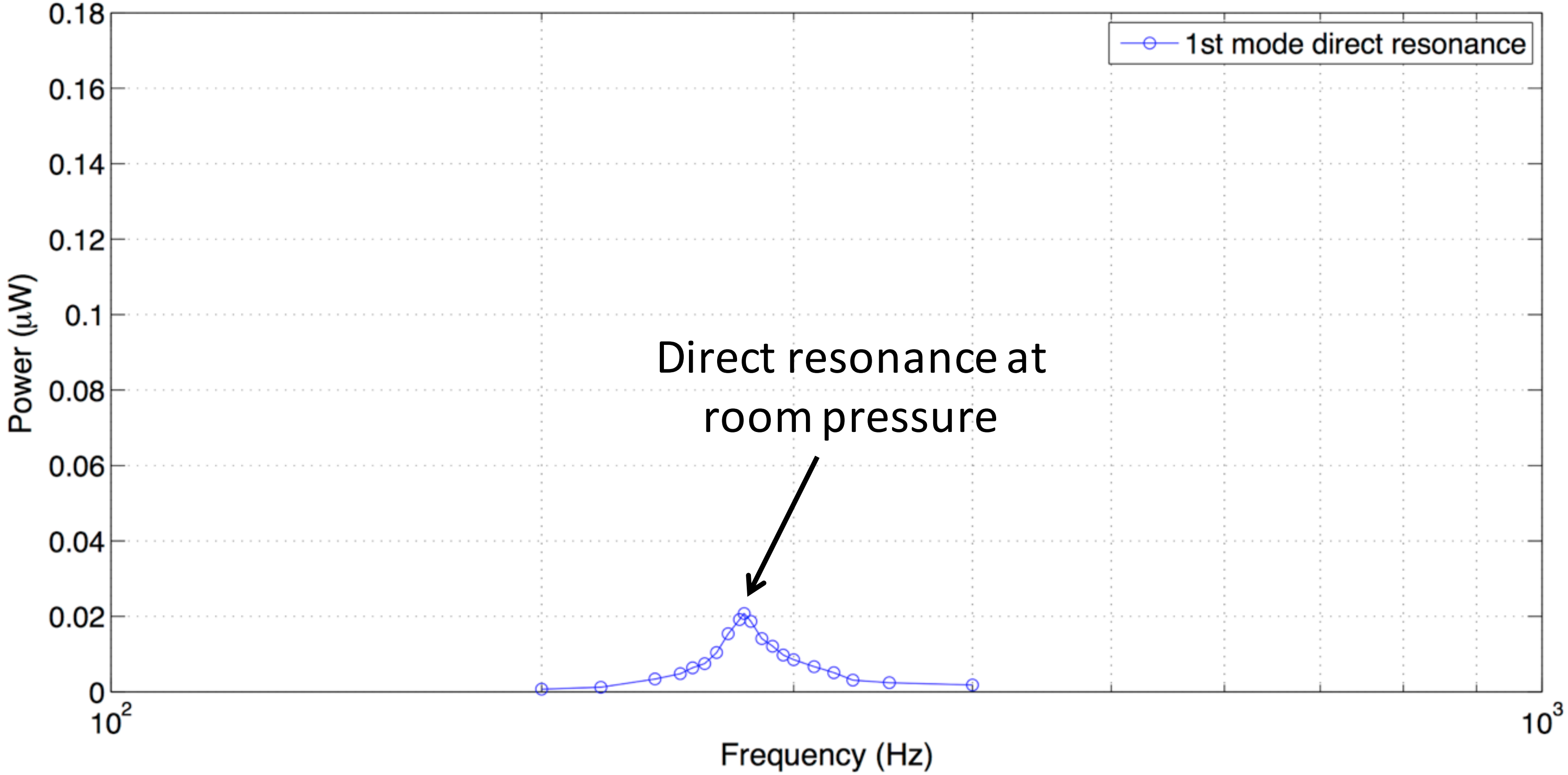


~An order of magnitude enhancement in amplitude and bandwidth



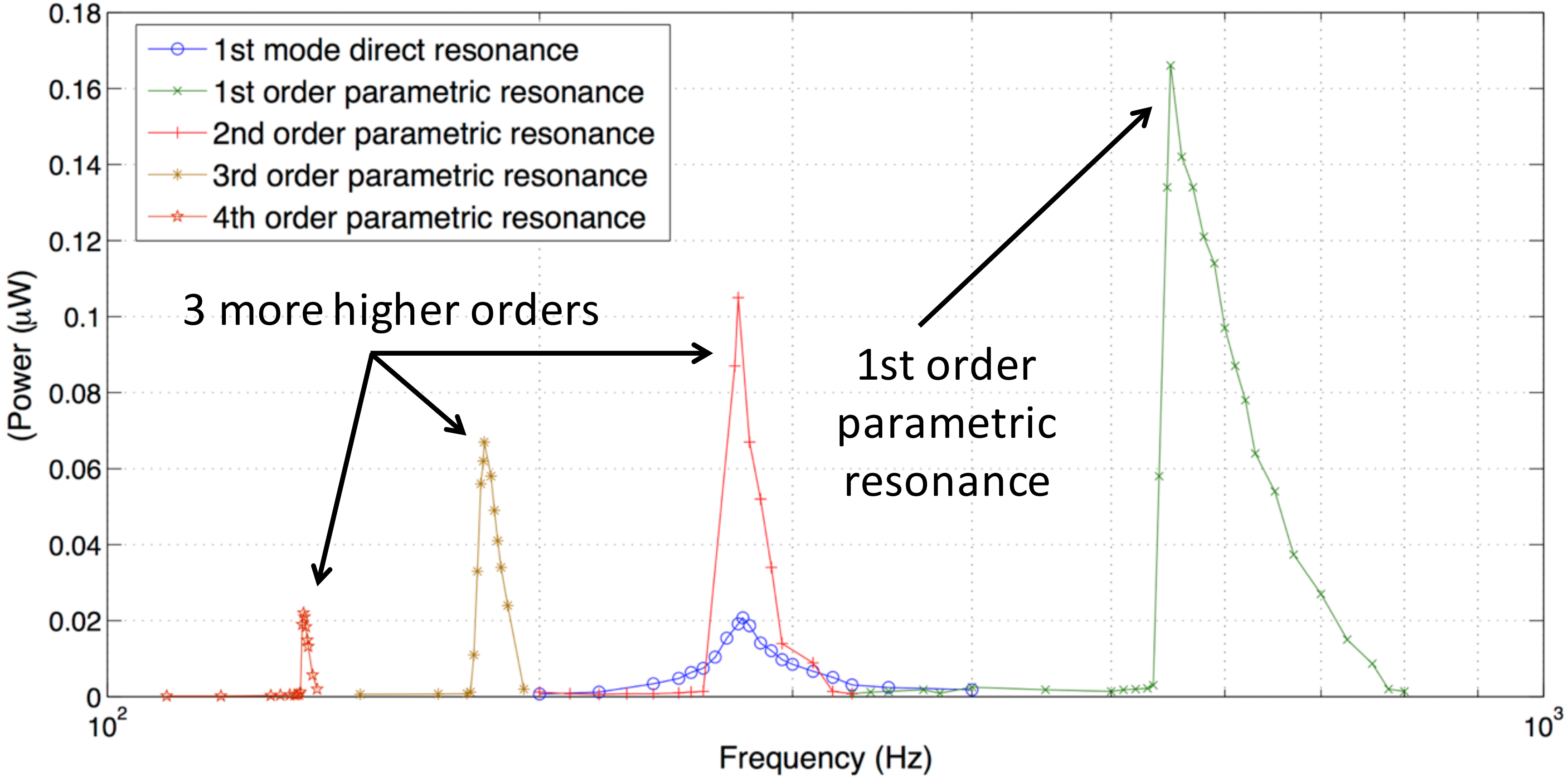
DOI: 10.1088/1742-6596/476/1/012126

Power response at room pressure for 0.5 g



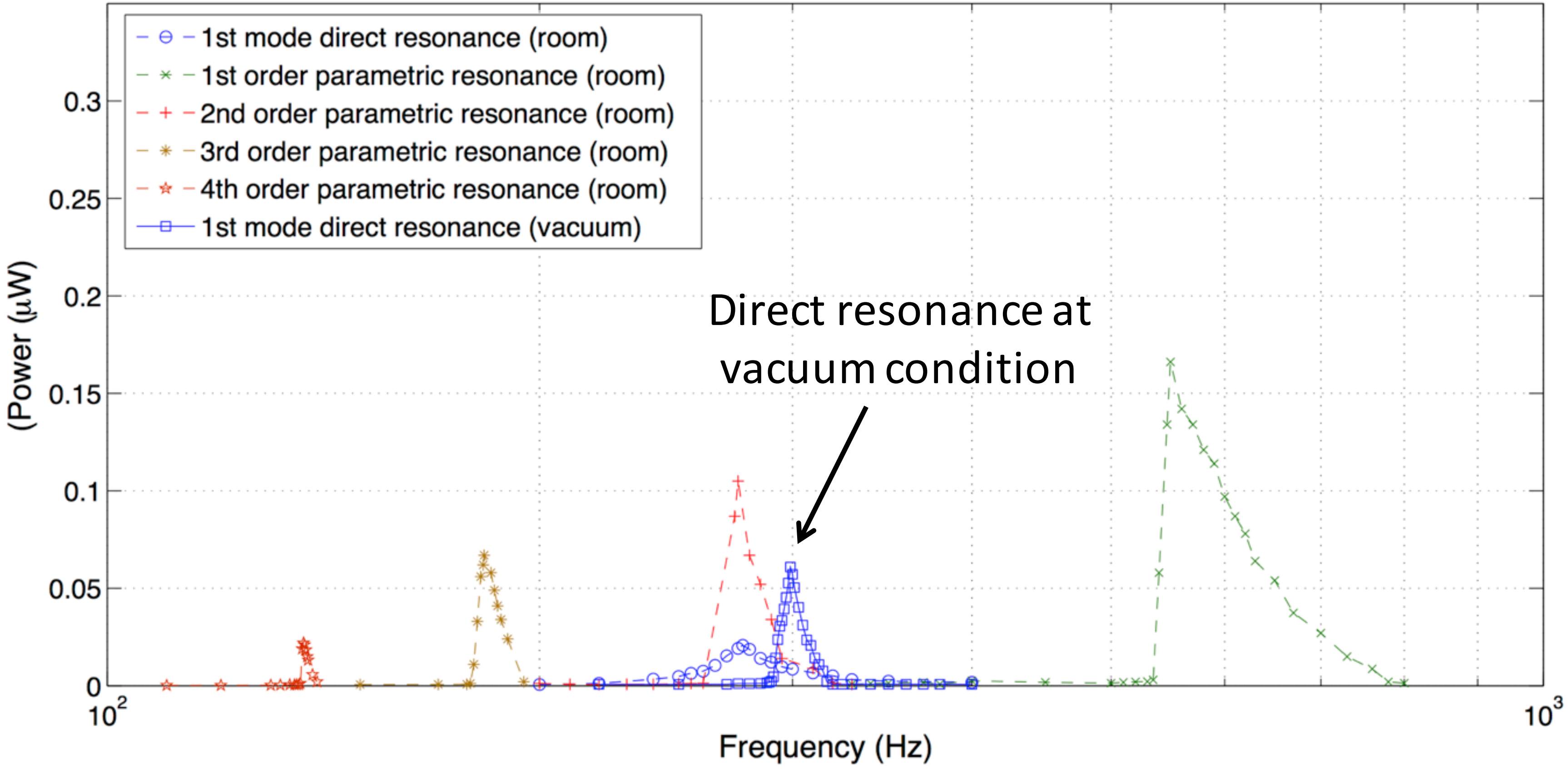
- 1st DR: 20.8 nW at 277 Hz with 40 Hz 3 dB bandwidth.

Power response at room pressure for 0.5 g



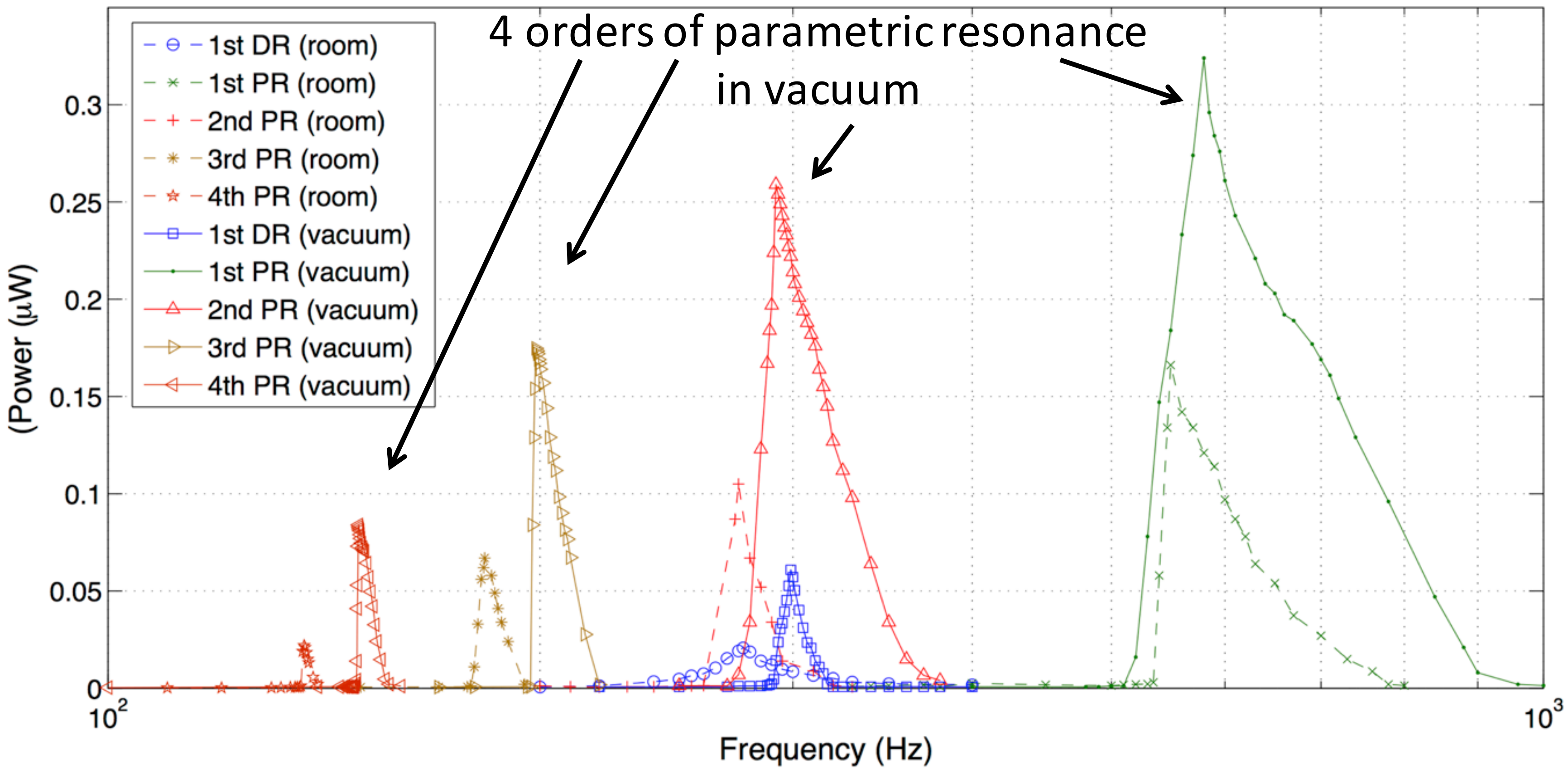
- 4 orders observed at $2f_n/n$, where n is order number.

Power response at vacuum for 0.5 g



- 1st DR: 60.9 nW at 299 Hz with 11 Hz 3 dB bandwidth.

Power response at vacuum for 0.5 g



- 1st order PR: 324 nW at 580 Hz with 160 Hz 3 dB bandwidth.

Room vs vacuum summary

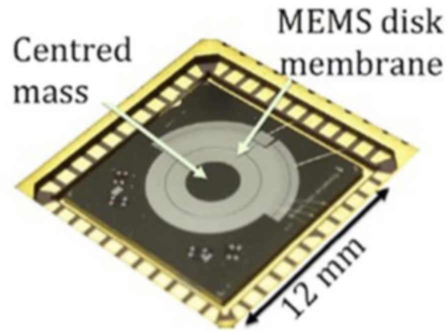
	Room pressure			**Vacuum packaged**		
	Excitation at 5.1 ms^{-2}		Initiation threshold (ms^{-2})	Excitation at 5.1 ms^{-2}		Initiation threshold (ms^{-2})
	Power (nW)	3 dB band (Hz)		Power (nW)	3 dB band (Hz)	
Direct	20.8	40	n/a	60.9	11	n/a
Parametric	166	80	1.57	324	160	0.98
		×2			×14.5	

- Broader frequency bandwidth for PR, but narrower for DR

Roadblocks in piezoelectric MEMS implementations

- Potentially achieve **higher power density** than electrostatic transducers
- Some materials, such as AlN, can withstand high temperature levels

- Initial spring designs results in strain concentration
  – not desirable for **piezoelectric transducer optimisation** over an area
- Membrane implementations without initial-springs observed record number of higher orders (n > 28), but peak power level was still relatively low ~μW



doi:10.1038/srep30167

Ultra high order parametric resonance in MEMS


SCIENTIFIC REPORTS

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Twenty-Eight Orders of Parametric Resonance in a Microelectromechanical Device for Multi-band Vibration Energy Harvesting

Received: 05 February 2016
Accepted: 28 June 2016
Published: 22 July 2016

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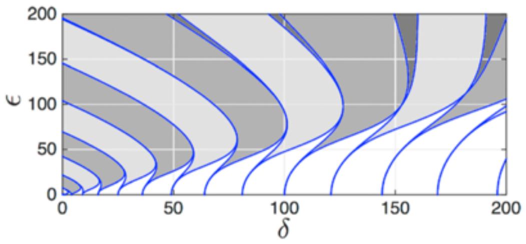

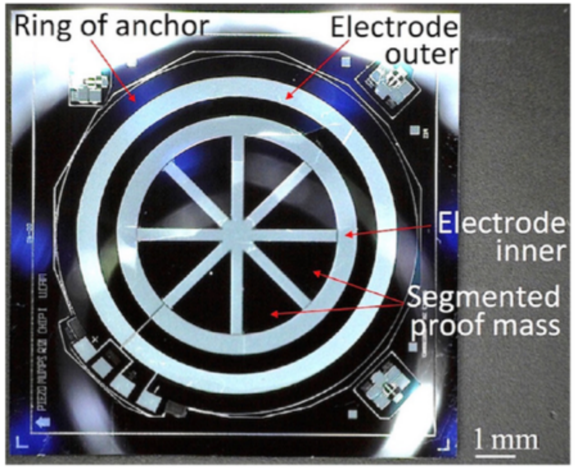

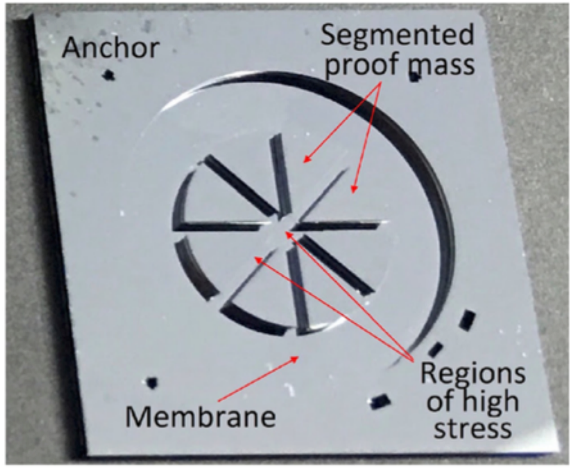

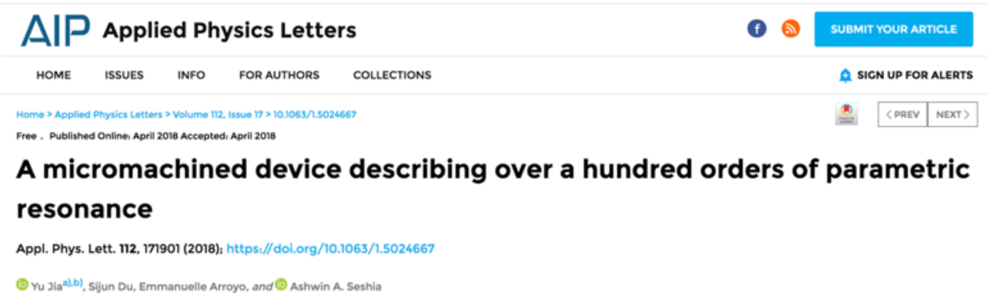
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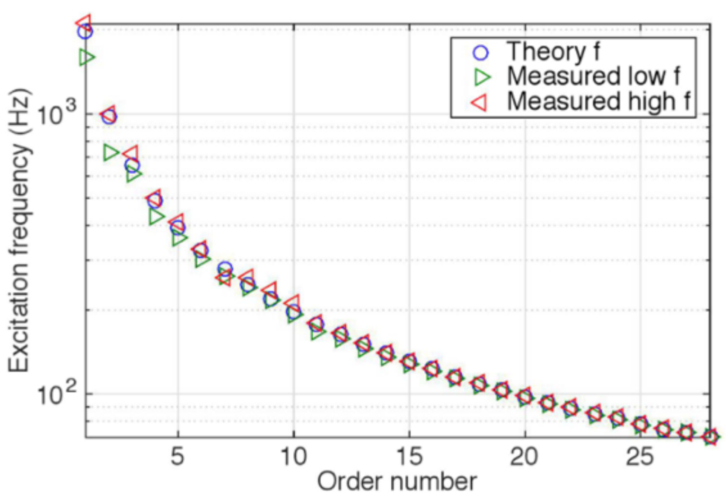
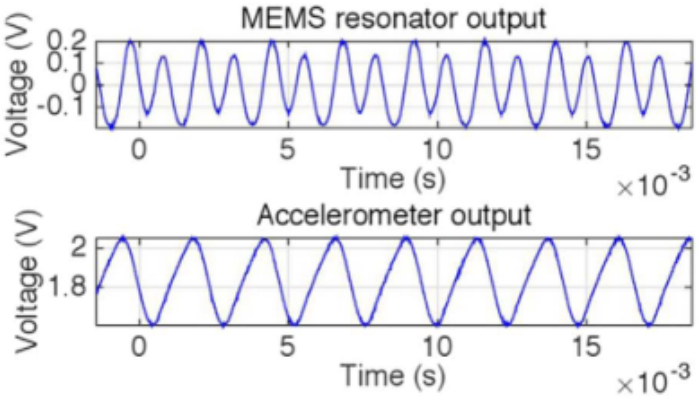
Free . Published Online: April 2018 Accepted: April 2018

A micromachined device describing over a hundred orders of parametric resonance

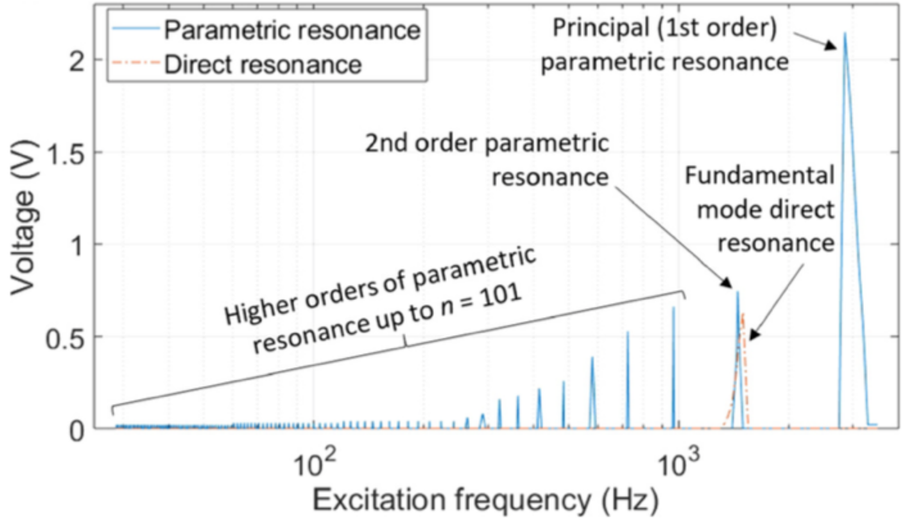
Appl. Phys. Lett. 112, 171901 (2018); https://doi.org/10.1063/1.5024667

Yu Jia[a),b)], Sijun Du, Emmanuelle Arroyo, and Ashwin A. Seshia





An example of the 4th order, where excitation frequency is half of the response

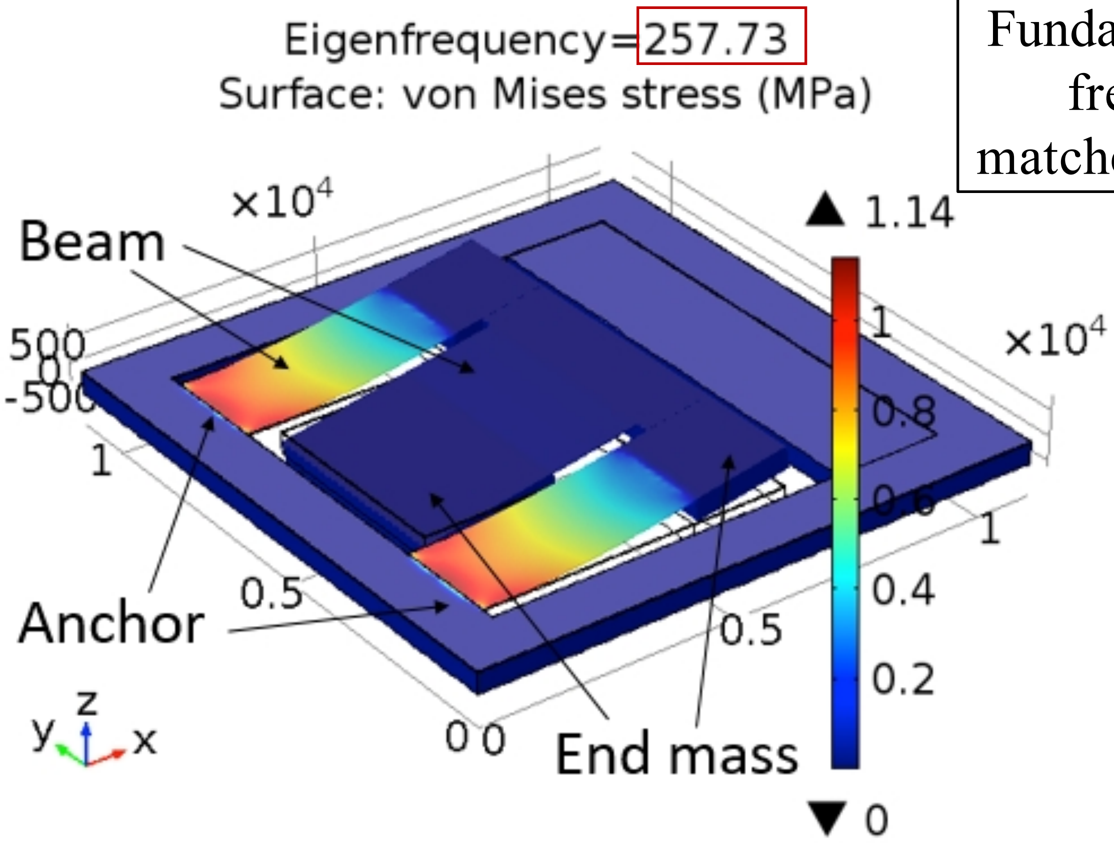


VEH application target for MEMS piezoelectric…

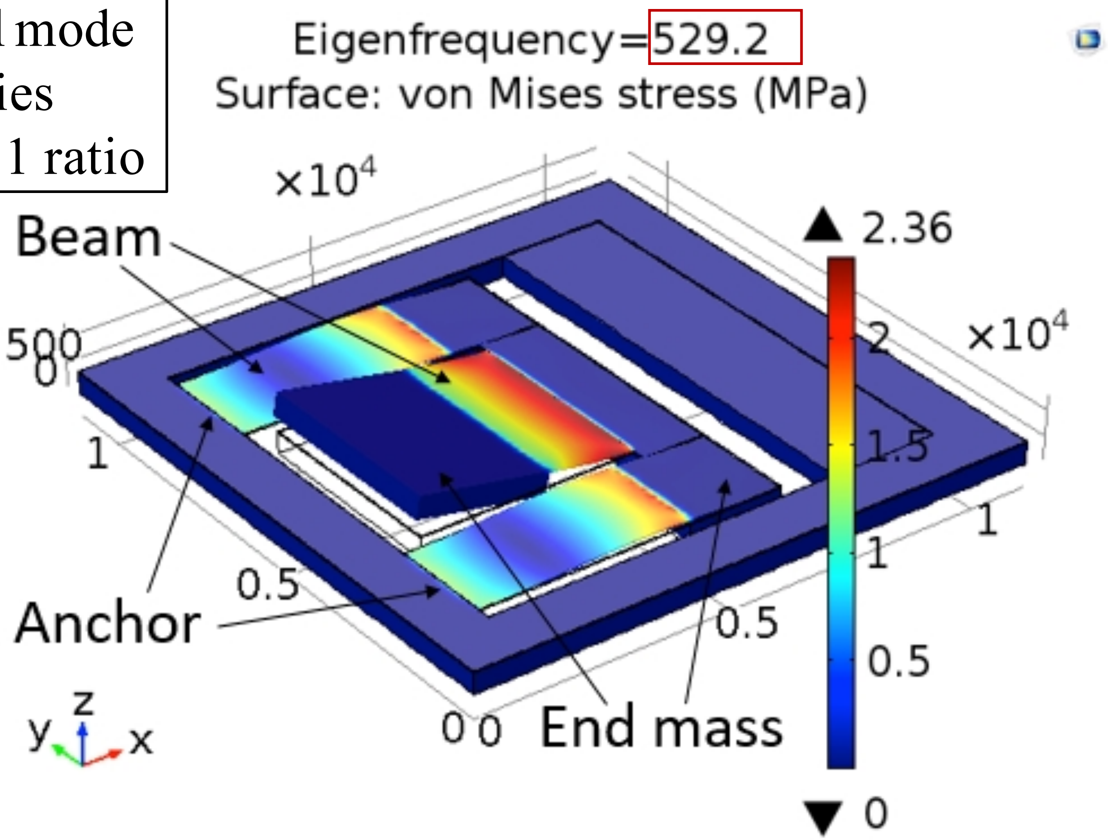
Activate parametric resonance to unlock the potential benefits of the instability nonlinearity regimes…

…**without sacrificing the strain energy distribution** across large area for optimal piezoelectric transduction.

Autoparametric MEMS design topology (2016-2017)



Fundamental mode frequencies matched to 2:1 ratio



Parametric excitation $\ddot{x}_2(t)$

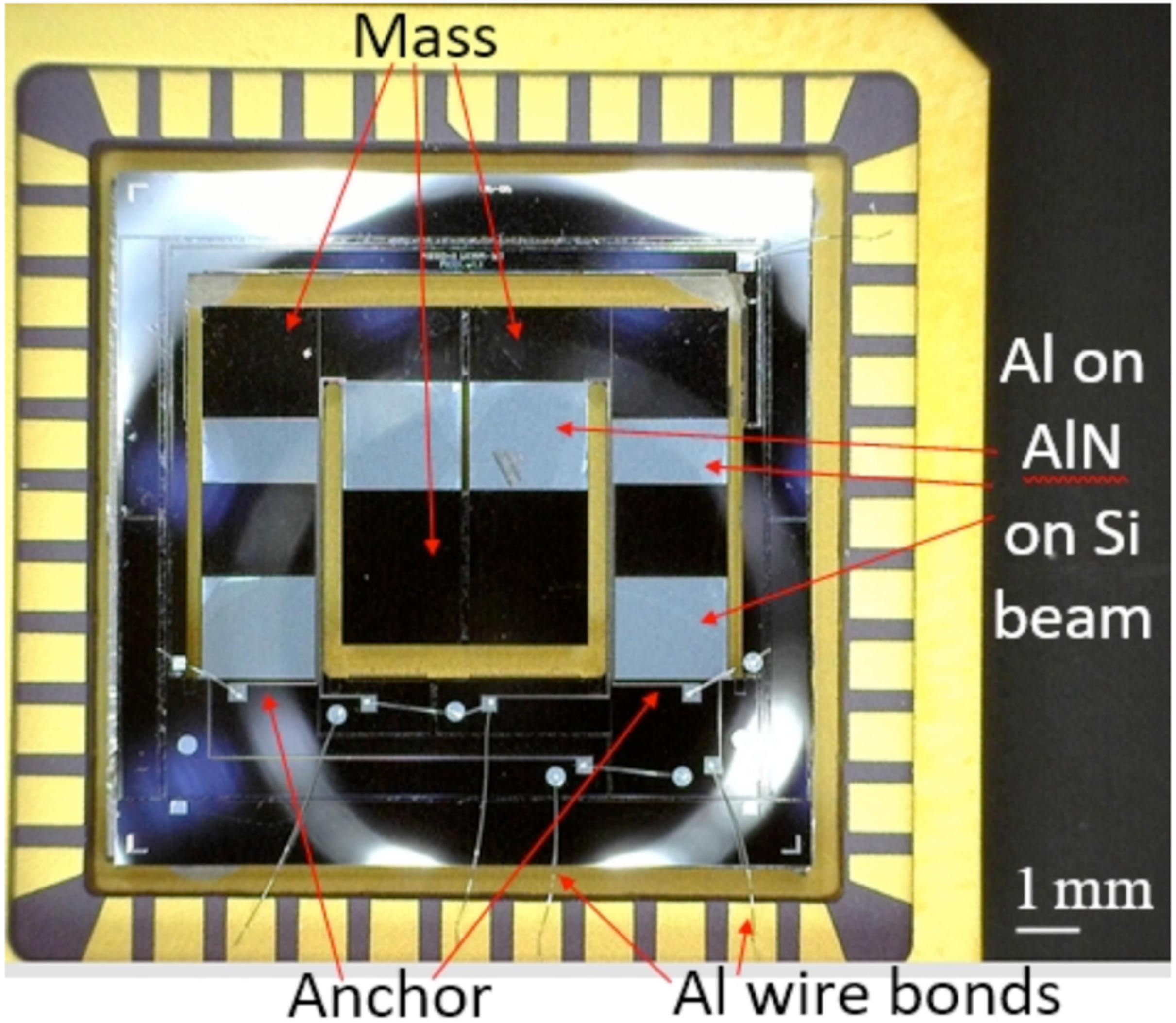
$$m(t)\,\ddot{x}_1 + c\,\dot{x}_1 + k(t)\,x_1 = 0 \longleftarrow m\,\ddot{x}_2 + c\,\dot{x}_2 + k\,x_2 = F(t)$$

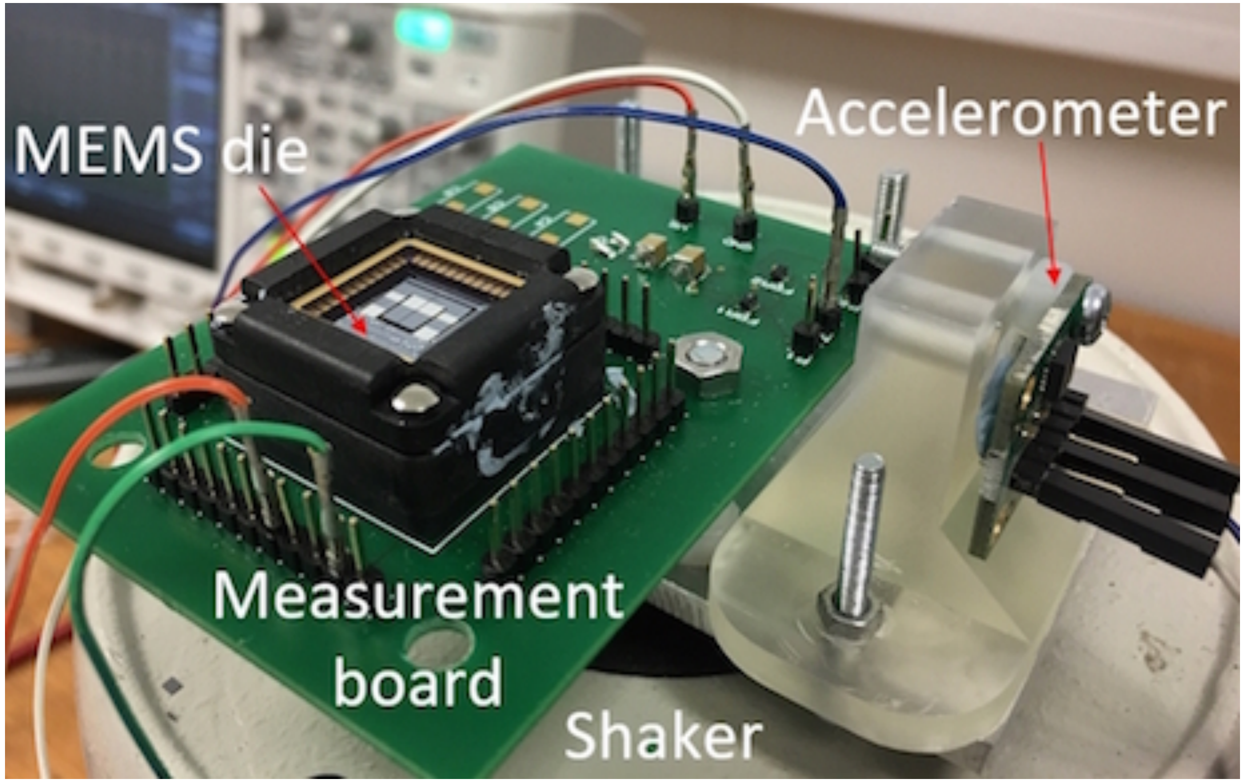
Primary cantilever beam

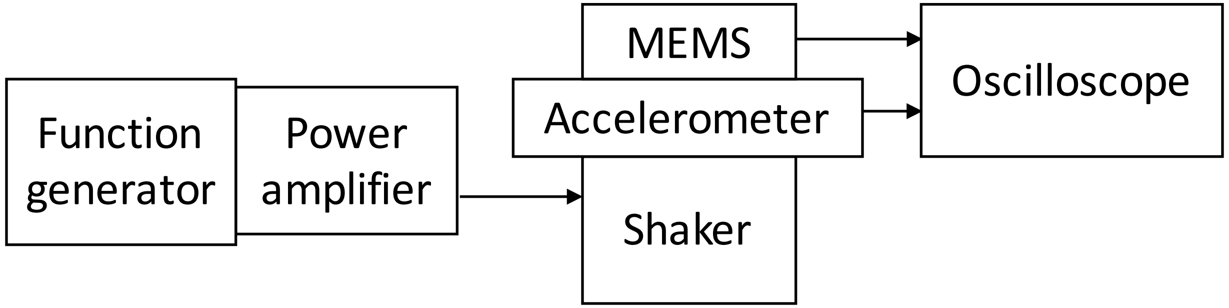
$\ddot{x}_2(t)$ modulates mass and stiffness at twice the fundamental frequency

Subsidiary cantilever beam

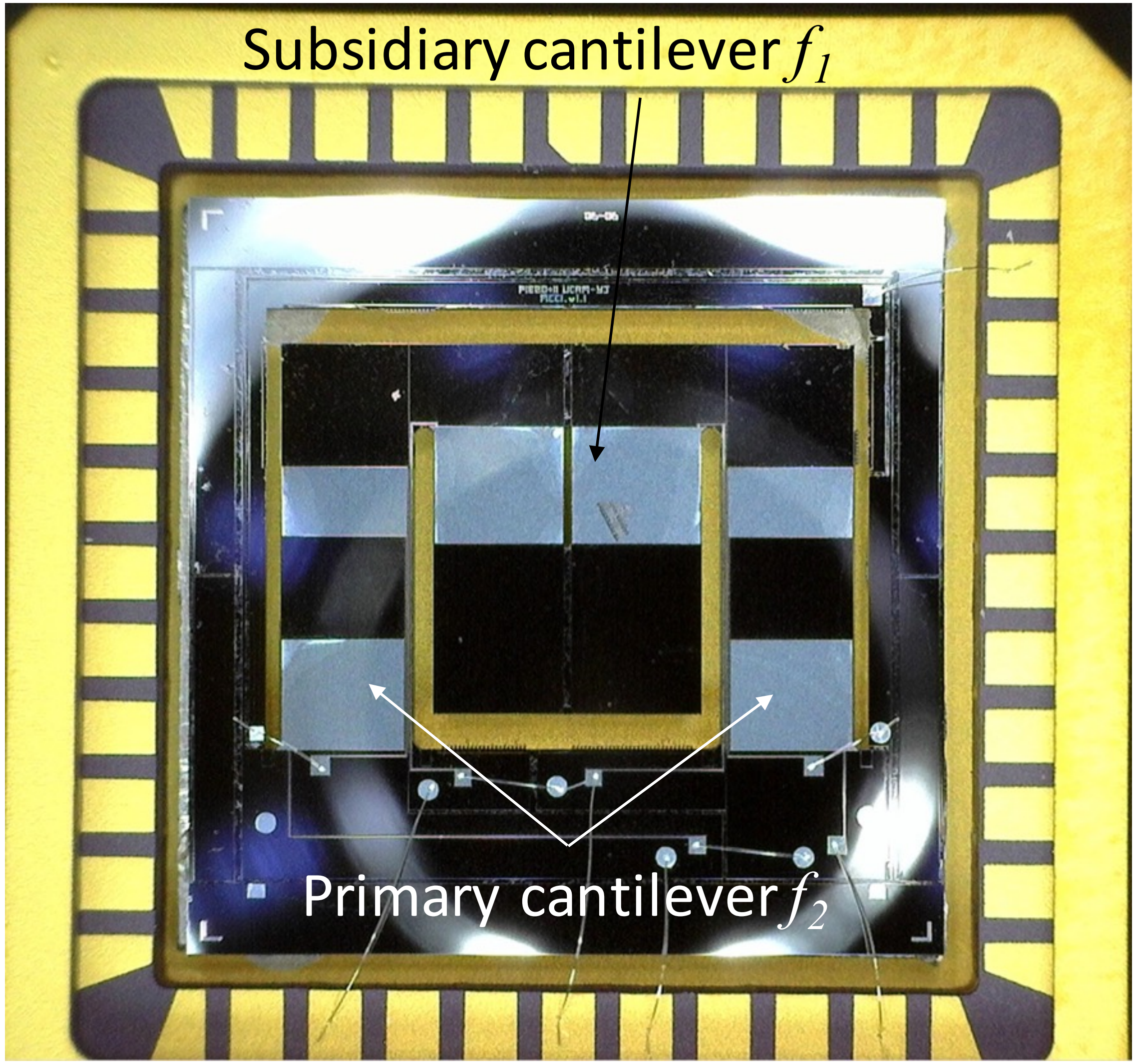
Device and experimentation







Device characterisation

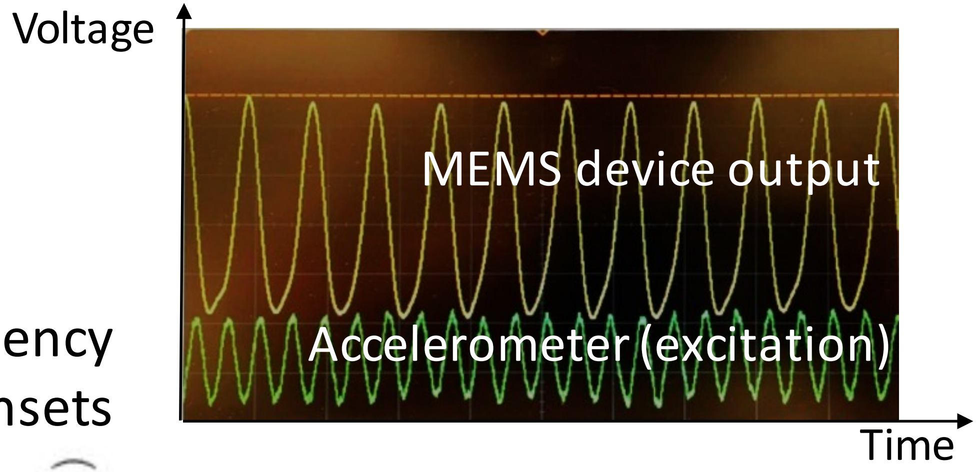


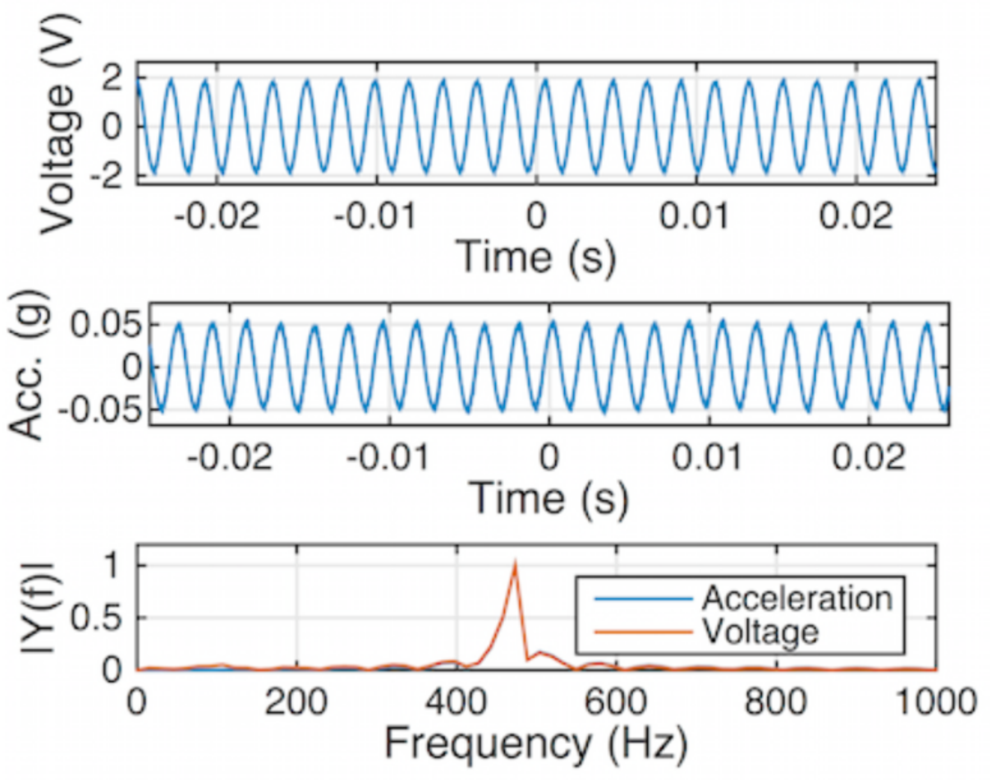
MEMS VEH devices	f_1 (Hz)	f_2 (Hz)	*Freq. Ratio*
Autoparametric tuned	449.3	224.2	2.0
Autoparametric de-tuned	474.6	224.2	2.1

- Frequency ratio varies between dies due to fabrication tolerances across the wafer
- Results from two devices shown here (table above), a device with de-tuned ratio and another device with well matched ratio

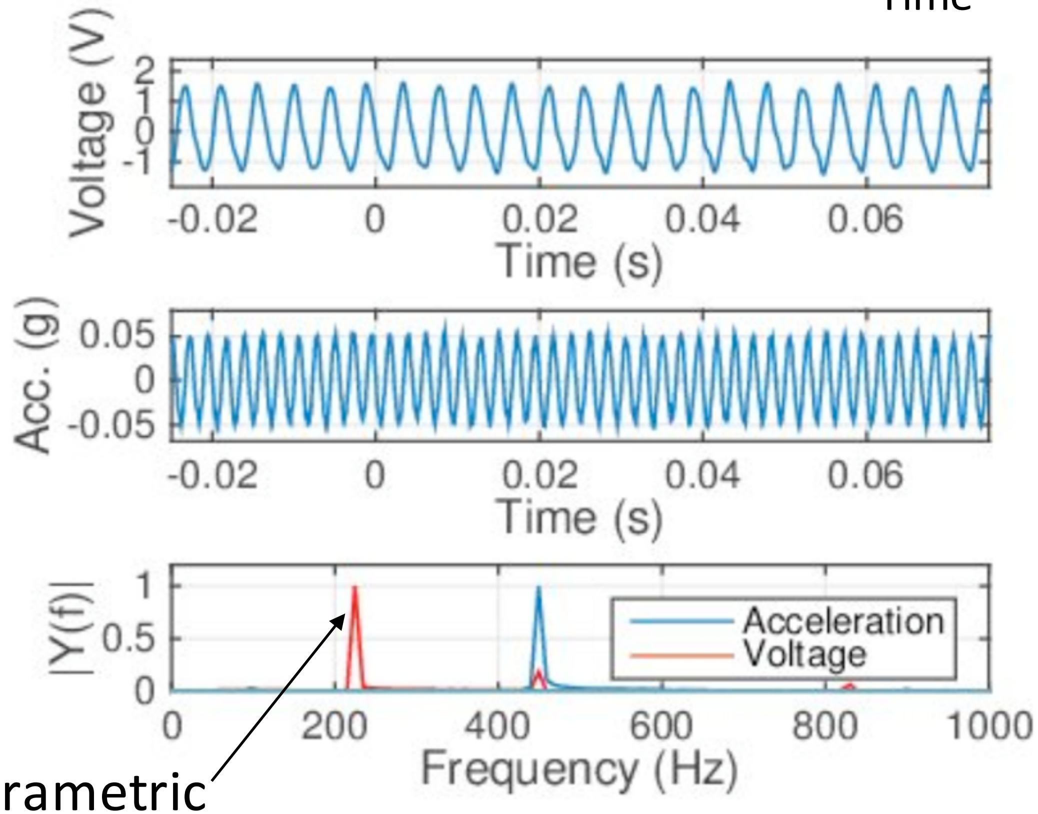
Device characterisation

Response at half the excitation frequency
if parametric resonance onsets





De-tuned device $2.1:1$

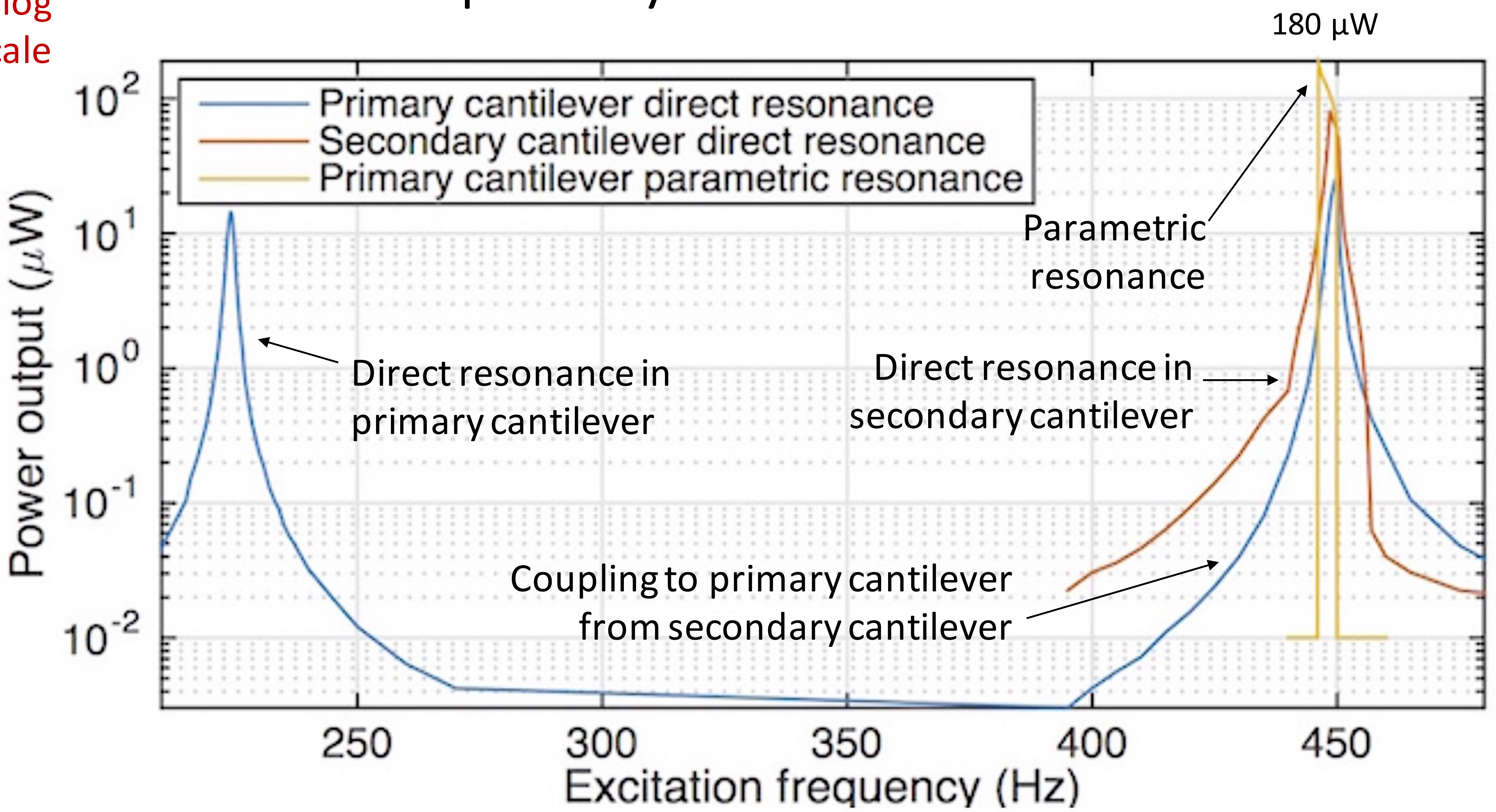


Parametric resonance

Tuned device $2:1$

Frequency characteristics

Note log scale



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8power
Cambridge spin-off

1 nW | 10 nW | 100 nW | 1 μW | 10 μW | 100 μW | 1 mW | 10 mW | 100 mW | 1 W

Achievements so far

Electrostatic (MEMS)

Electromagnetic (macro)

Piezoelectric (MEMS)

Electromagnetic (macro) Robustness

Development plan

A tool for fundamental physical research

Piezoelectric (MEMS)

Continuing interest for academic research

Piezoelectric (MEMS)

New dedicated process validated, and under further development, including robustness

Conclusion

- Parametric resonance can potentially improve **both power amplitude** and **frequency bandwidth** at the same time
- Its initiation is non-trivial and involves design and manufacturing **complexities**
- Piezoelectric MEMS autoparametric **design** without compromising on transducer power output has been recently demonstrated
- **Ultra high order** parametric resonance can be unlocked in MEMS
- Ongoing and future work involves optimising the **process** stack, improving **robustness** and real world vibration testing

Contributors to various stages of the research

- *VEH & MEMS*
  - Ashwin A. Seshia
  - Sijun Du
  - Emmanuelle Arroyo
  - Shao-Tuan Chen
- *Civil and bridges*
  - Kenichi Soga
  - Campbell Middleton
- *WSN*
  - Jize Yan
  - Tao Feng
  - Paul Fidler
  - David Rodenas-Herraize
  - Andrea Gaglione
  - Cecilia Mascolo
- *CMOS-MEMS oscillator*
  - Cuong Do
  - Xudong Zou

Thank you for your attention