Design and optimisation of miniature vibration energy harvesters to supply low-power sensing systems

Nanoscience Centre
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Energy Harvesting Network
04/04/17

Optimisation of a vibration energy harvester

To target highest power and practical applications

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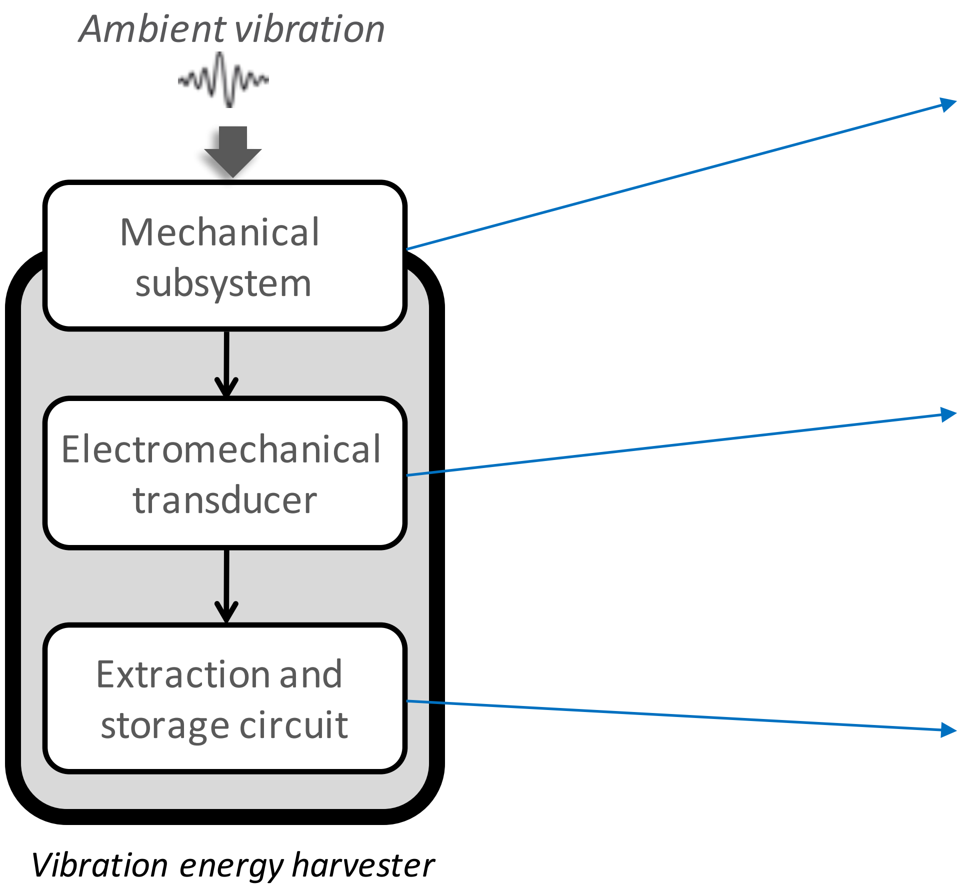


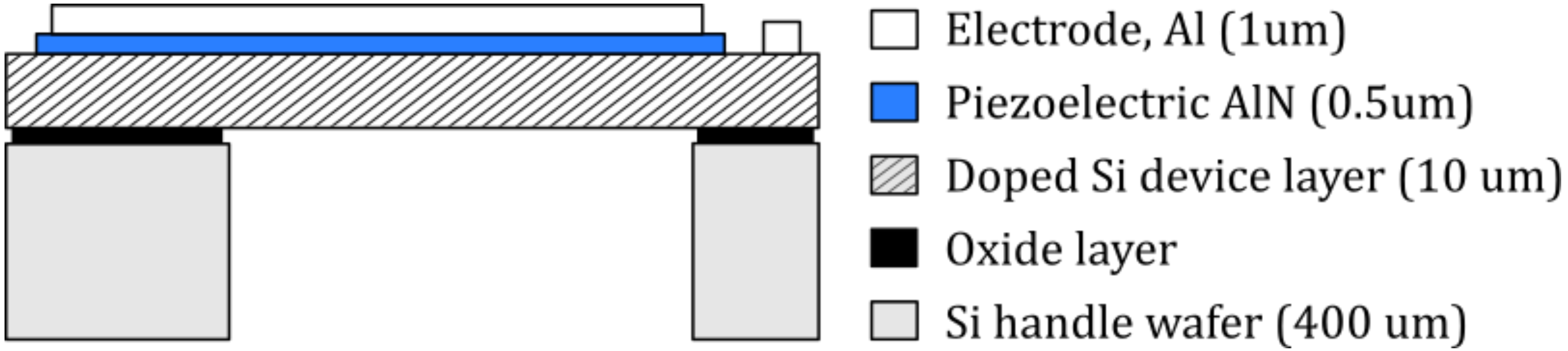
- Parametric resonance
- Nonlinear mechanical structures
- Nonlinear damping

- Piezoelectric layer dimensions optimisation

- Split electrodes
- Optimal electrode coverage
- Nonlinear extraction circuit

Optimisation of MEMS energy harvesters

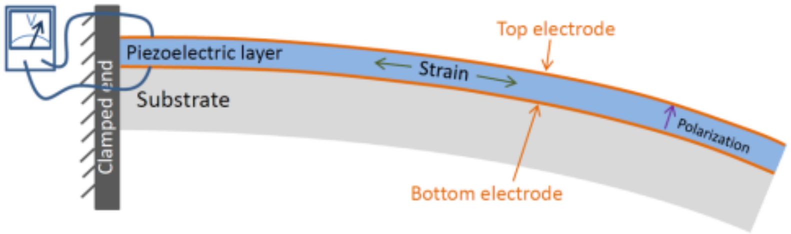
Piezoelectric cantilever

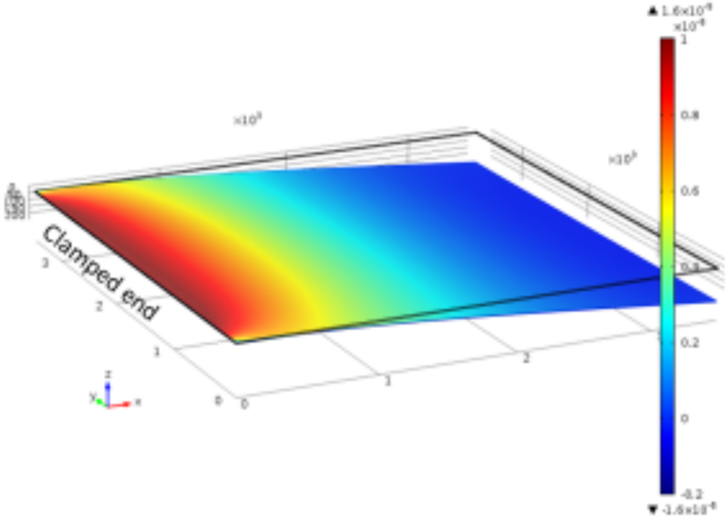


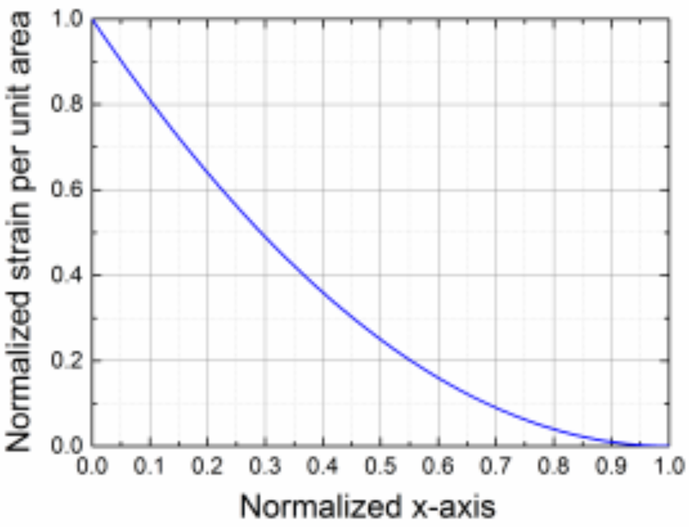
- Commonly used structure for energy harvesting
- Compatible with miniaturisation
- Objective: 100uW for classical sensors networks applications

Optimisation of MEMS energy harvesters

Optimisation of the electrode size





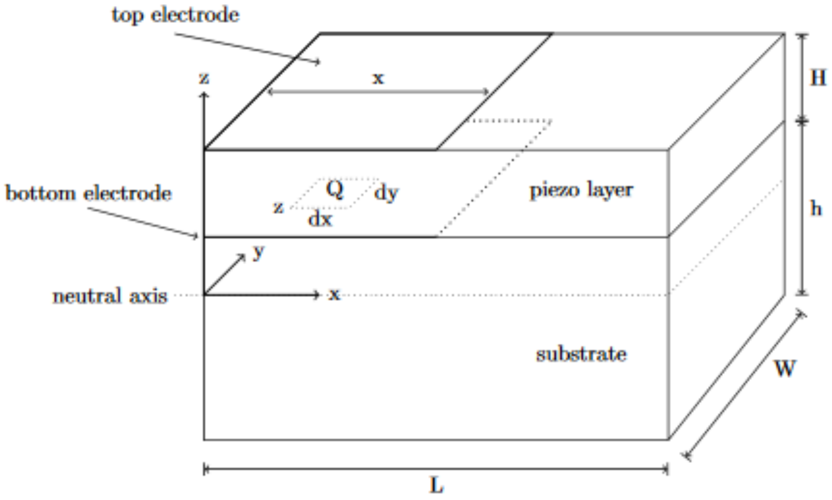


- Taking advantage of the higher strain regions (close to the anchor)

Sijun Du, Yu Jia and Ashwin Seshia, Maximizing Output Power in a Cantilevered Piezoelectric Vibration Energy Harvester by Electrode Design, 2015

Optimisation of MEMS energy harvesters

Optimisation of the electrode size



Model based on beam theory

$$C_P = \varepsilon_r \varepsilon_0 \frac{xW}{H}$$

$$R_P = \rho \frac{H}{xW}$$

$$P = \frac{1}{2} I_0^2 Z_{int}$$

- Taking advantage of the higher strain regions (close to the anchor)

- Larger electrode area = larger capacitance and smaller resistance
  = smaller internal impedance

Sijun Du, Yu Jia and Ashwin Seshia, Maximizing Output Power in a Cantilevered Piezoelectric Vibration Energy Harvester by Electrode Design, 2015

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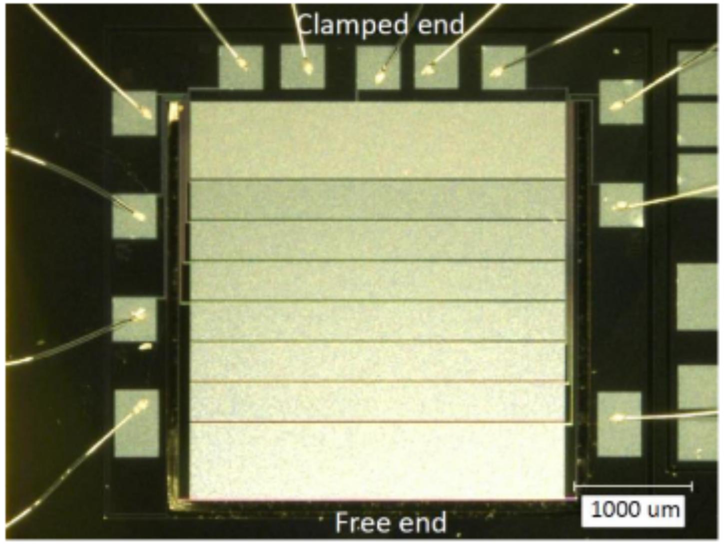
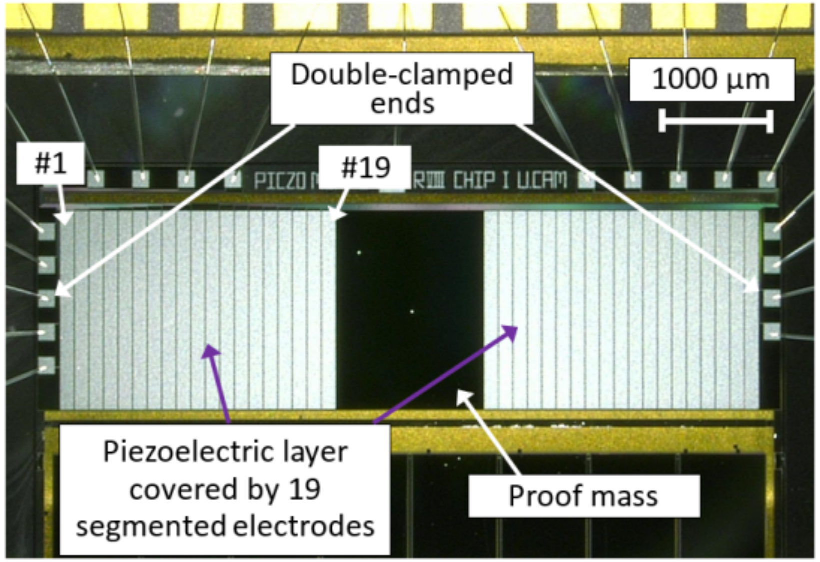


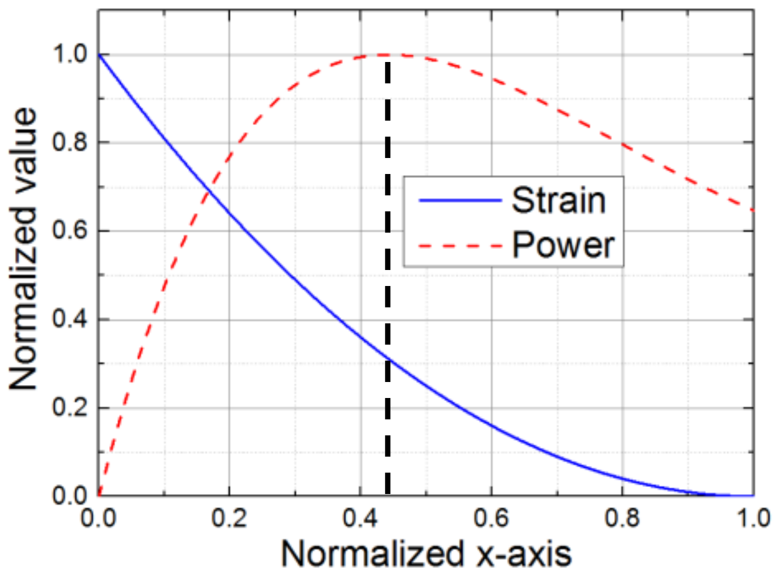
Experimental validation

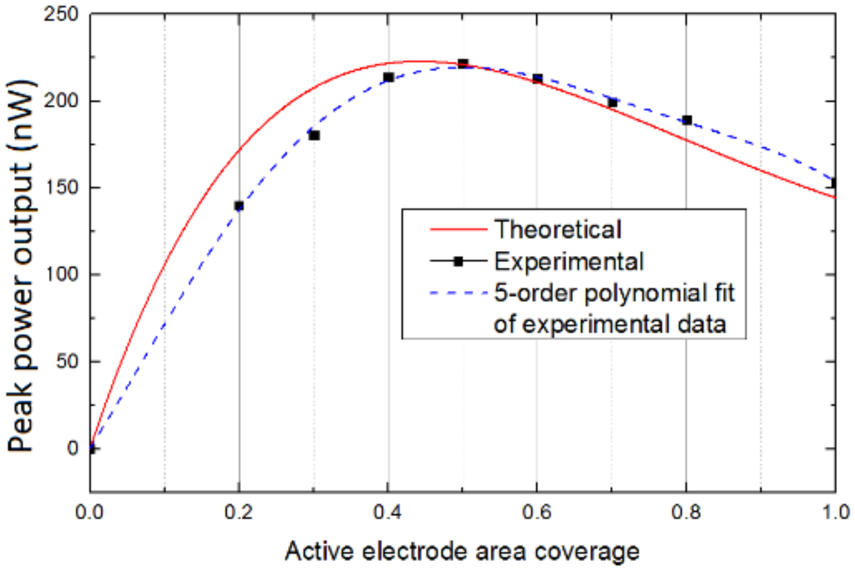


- Finding the optimal electrode length x: compromise between small capacitance and larger area covering the strain.

Optimisation of MEMS energy harvesters

Optimisation of the electrode size



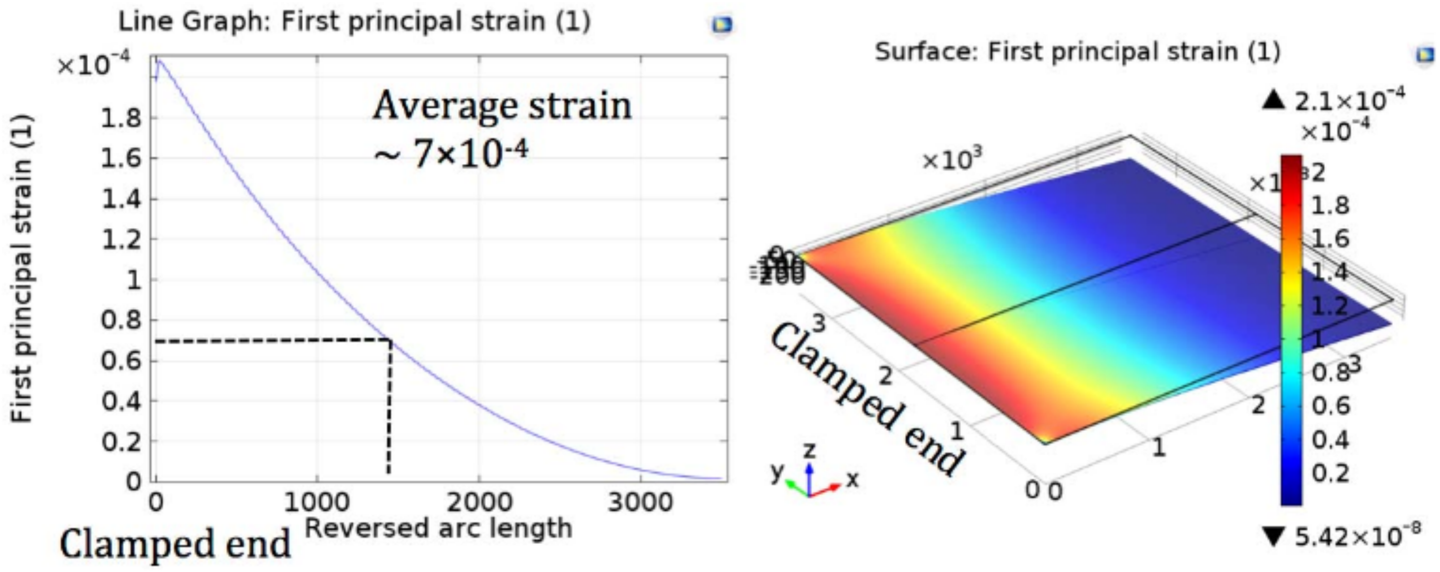


- When designing the cantilever:
  1- Detect the areas corresponding to less than 31% of the maximum bending stress (here corresponding to 44% of the total length)
  2- This area when covered by electrode contributes negatively to the output power

Sijun Du, Yu Jia and Ashwin Seshia, Maximizing Output Power in a Cantilevered Piezoelectric Vibration Energy Harvester by Electrode Design, 2015

Optimisation of MEMS energy harvesters

Piezoelectric cantilever: strain repartition

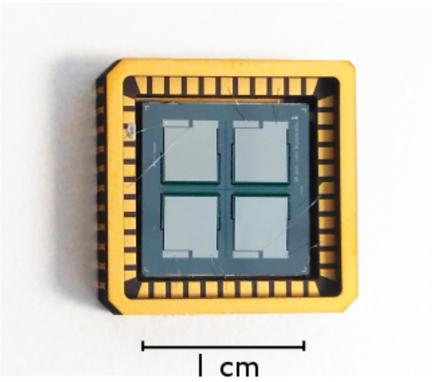


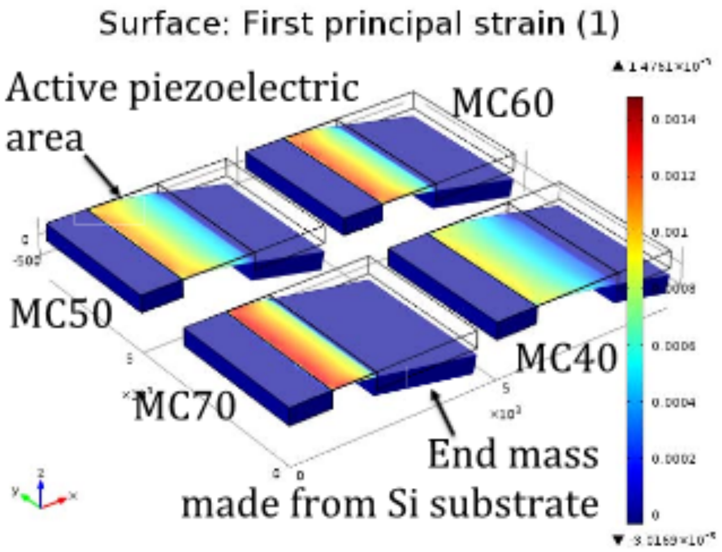
- Higher strain close to the clamped end
- The first third of the beam close to the clamped end contributes positively to the average strain
- Added proof mass to increase the compliance without compromising the average strain

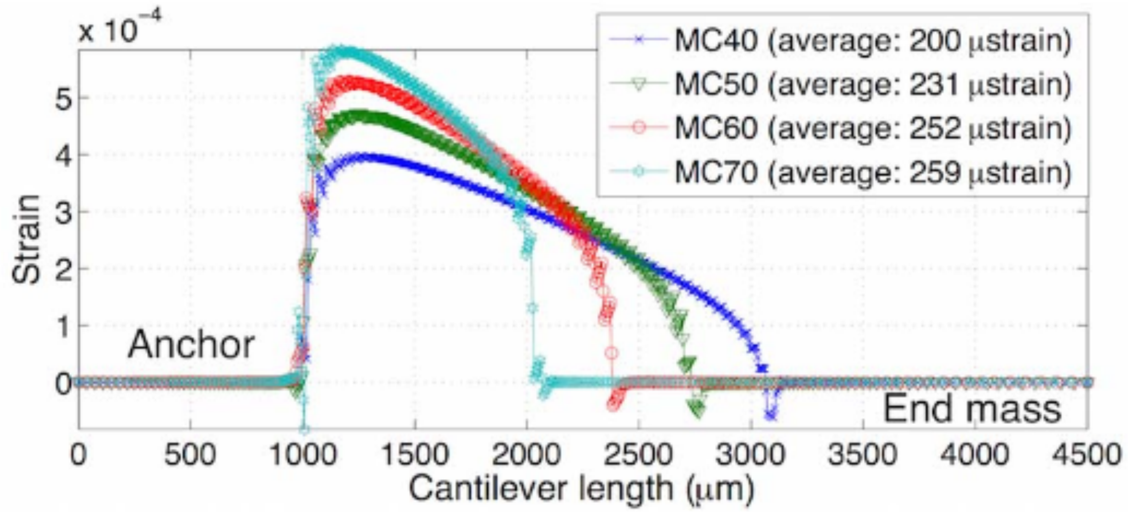
Y. Jia, A. Seshia, Power Optimization by Mass Tuning for MEMS Piezoelectric Cantilever. Vibration Energy Harvesting, 2016

Optimisation of MEMS energy harvesters

Optimisation of the mass-to-beam ratio







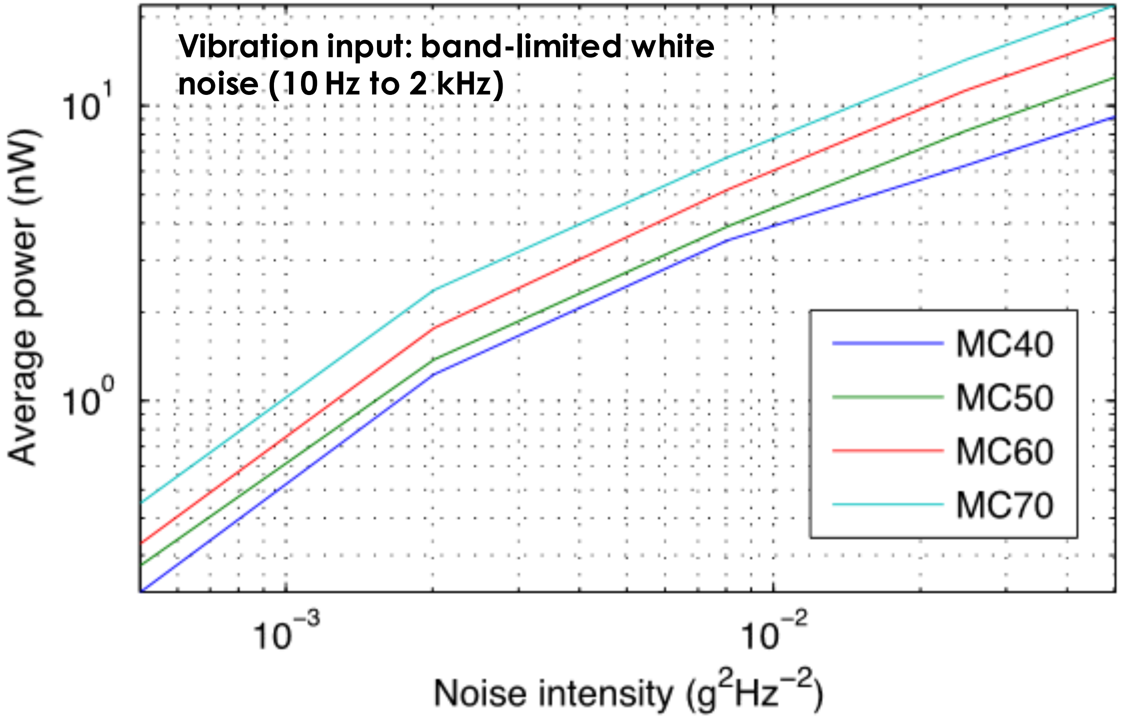
- Four cantilevers with different mass sizes :

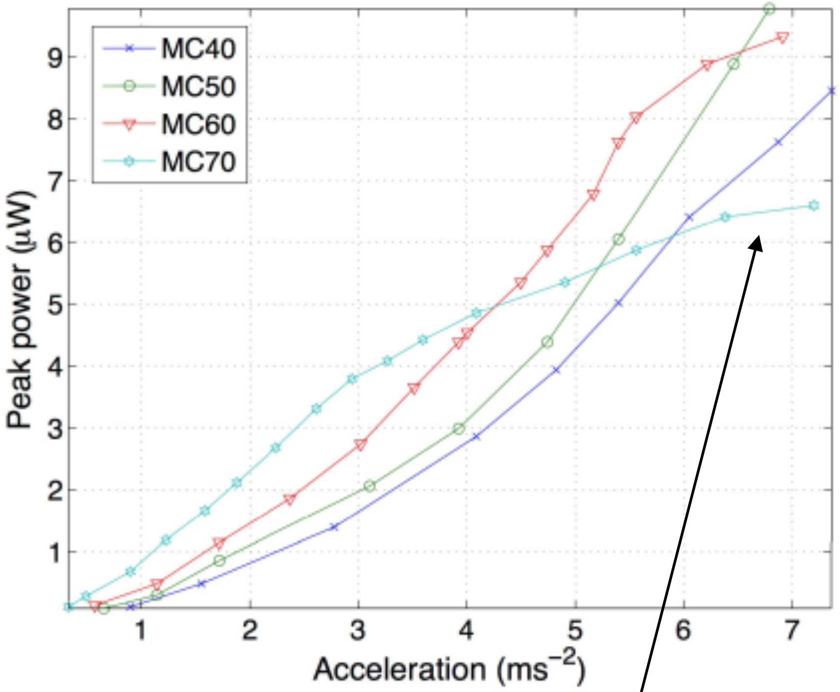
  40%, 50%, 60% and 70% of the total length

Y. Jia, A. Seshia, Power Optimization by Mass Tuning for MEMS Piezoelectric Cantilever. Vibration Energy Harvesting, 2016

Optimisation of MEMS energy harvesters

Optimisation of the mass-to-beam ratio



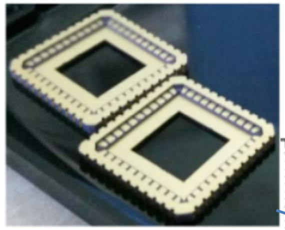


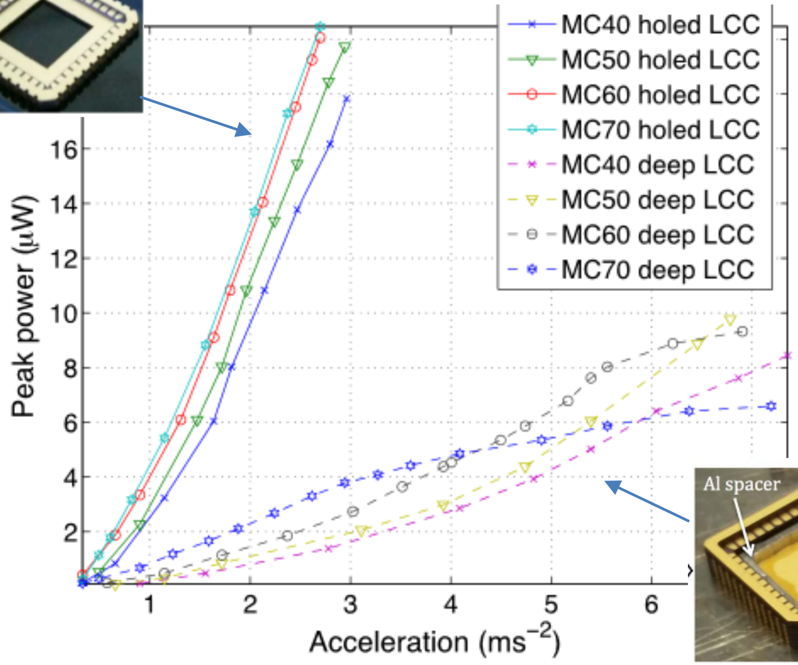
- Optimal proportion: mass size ~70% or 60% of the cantilever length
- Larger mass also increases squeeze film effect and nonlinear damping effects

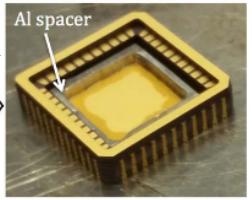
Y. Jia, A. Seshia, Power Optimization by Mass Tuning for MEMS Piezoelectric Cantilever. Vibration Energy Harvesting, 2016

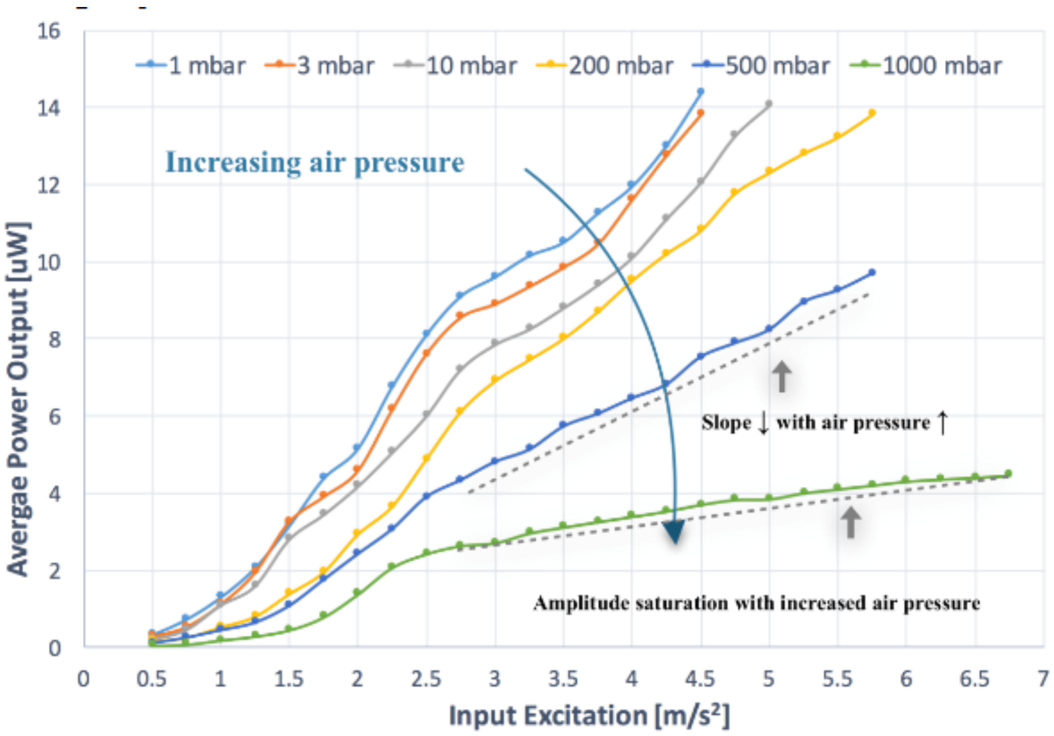
Optimisation of MEMS energy harvesters

Nonlinear damping for failure prevention









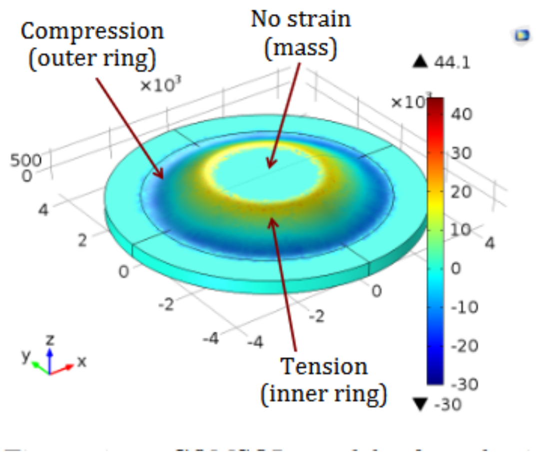
- Include damping into the design of a harvester
- Using the fracture limit of cantilever to calculate the optimal damping for a given acceleration profile

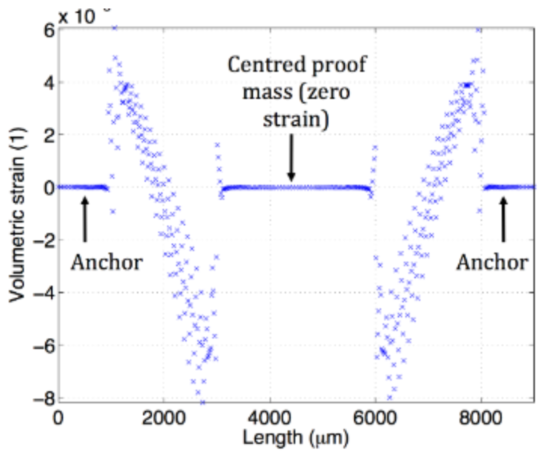
S. Tuan Chen, S. Du, E. Arroyo, Y. Jia and Ashwin Seshia, Utilising Nonlinear Air Damping as a Soft Mechanical Stopper for MEMS Vibration Energy Harvesting, 2016

Optimisation of MEMS energy harvesters

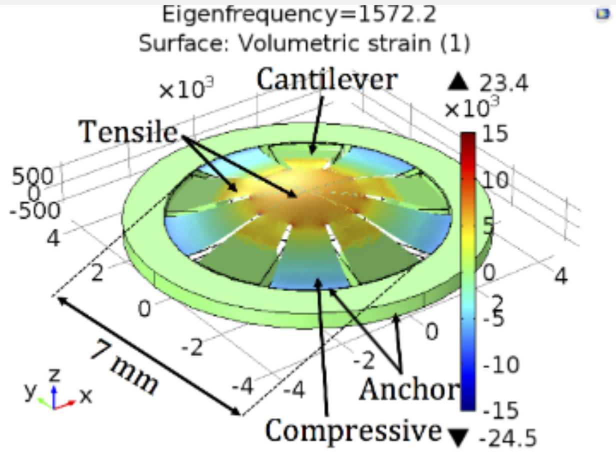
Innovative geometries

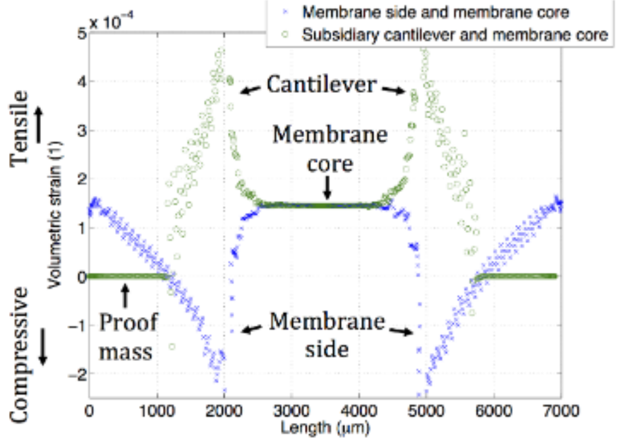
Membrane





Cantilevers on membrane





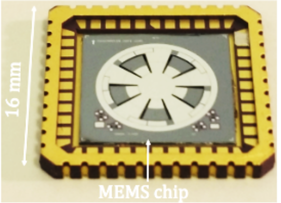
- Optimised for wide band operation and higher power
- Taking advantage of the higher strain at the middle of the membrane

Y. Jia, S.Du, A. Seshia, Cantilevers-on-membrane design for broadband MEMS piezoelectric vibration energy harvesting, 2015

Optimisation of MEMS energy harvesters

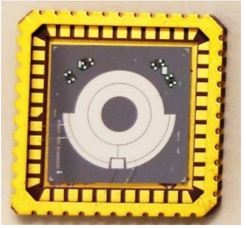
Innovative geometries

Cantilevers on membrane

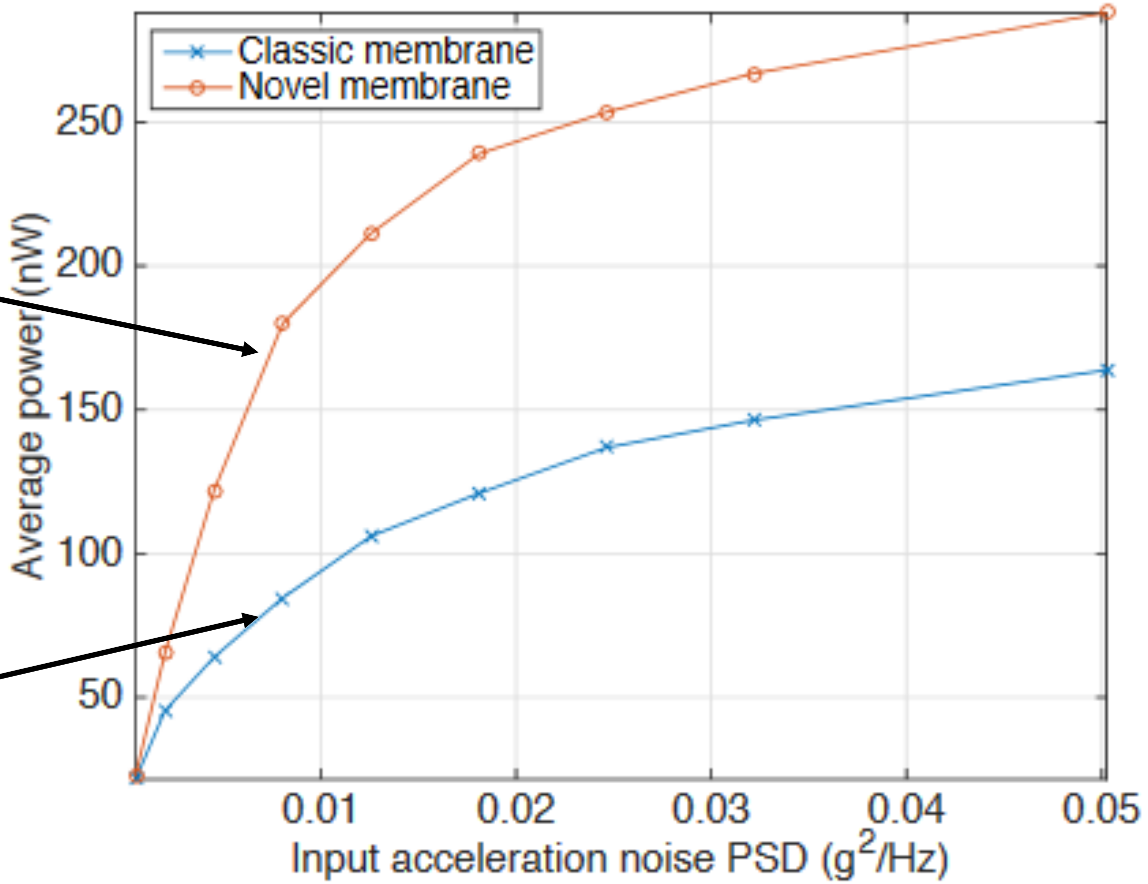


1400 Hz
280Hz -> 320 Hz

Membrane



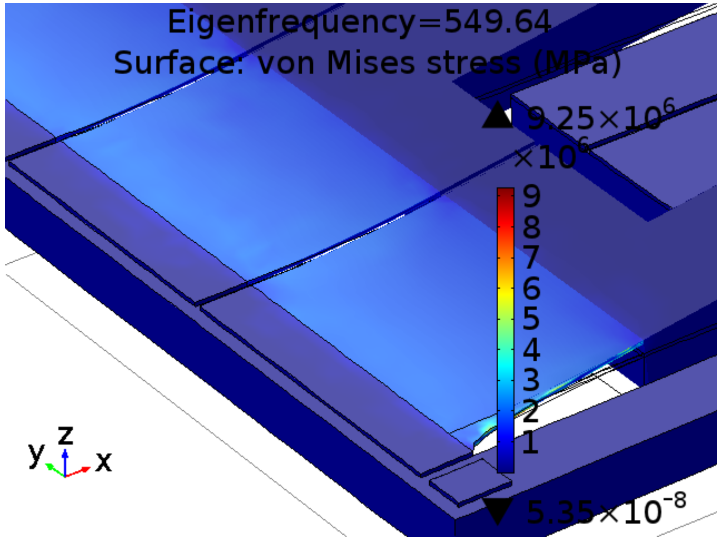
1200 Hz

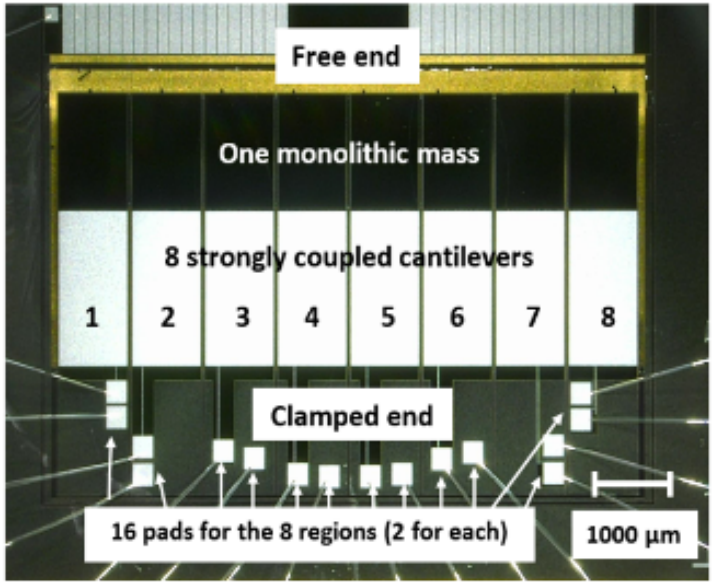


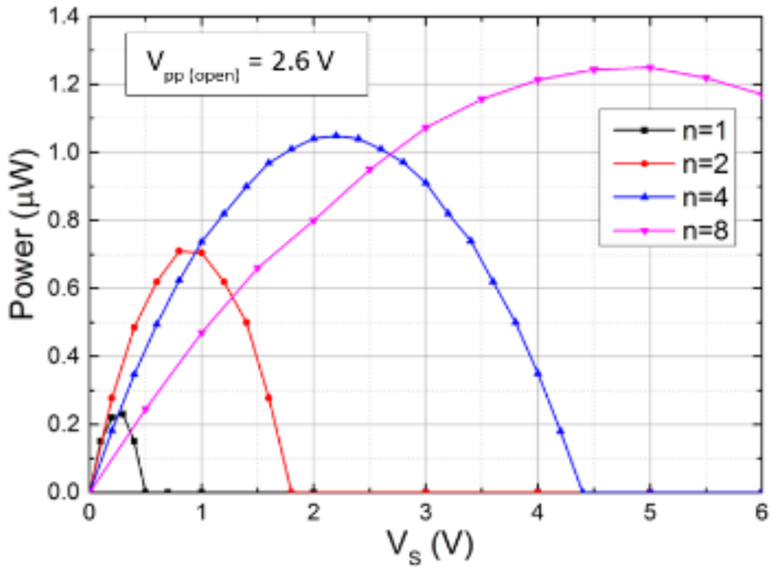
Y. Jia, S.Du, A. Seshia, Cantilevers-on-membrane design for broadband MEMS piezoelectric vibration energy harvesting, 2015

Optimisation of the electronics

Split electrodes for power optimisation





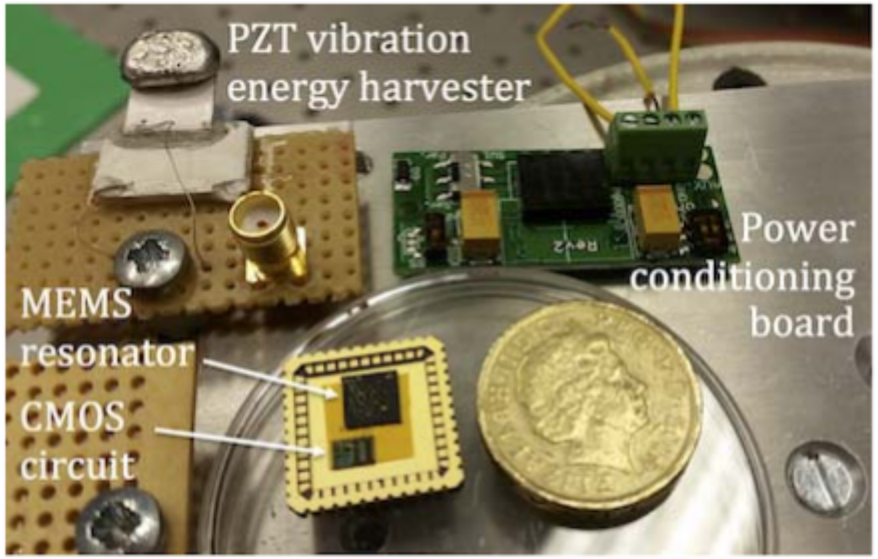


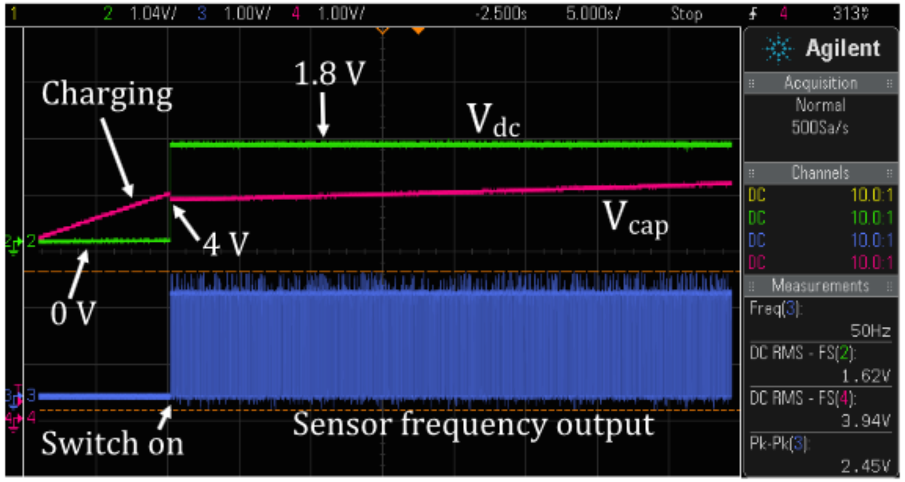
- Splitting the electrode into 8 regions in series can increase the output power by up to 5.4
- Addresses the issue of the high threshold voltage that exists in a full-bridge rectifier (FBR)

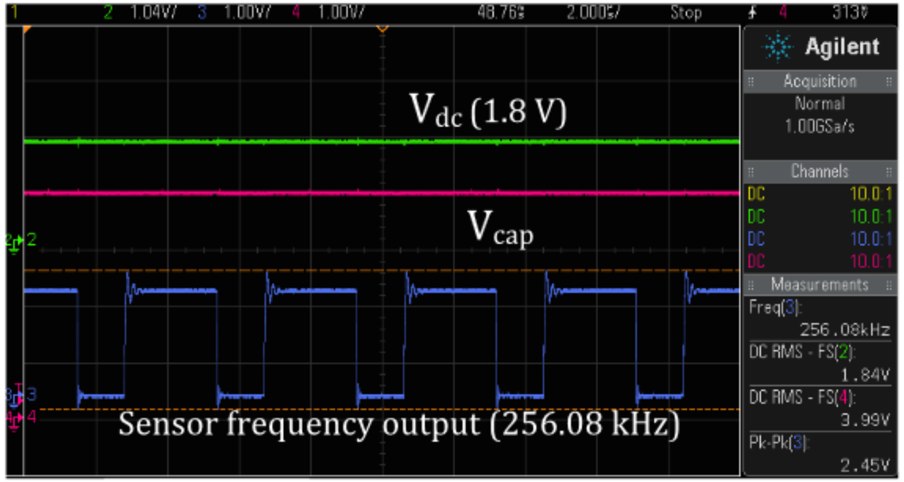
S. Du, S. Chen, Y. Jia, E. Arroyo and A. Seshia , Connection configurations to increase operational range and output power of piezoelectric MEMS vibration energy harvesters, 2016

Applications of MEMS energy harvesters

Powering a strain gauge







- Strain gauge: micro-fabricated double-ended tuning fork (DETF) resonator
- Power consumption:
  1.89μW at a supply voltage of 1.8 V+ ~60μW from cable loading
- Harvester power generation: 187μW at 11.4 ms−2 leading to 81μW after electronics

Yu Jia, Cuong D. Do, Xudong Zou, and Ashwin A. Seshia, A Hybrid Vibration Powered Microelectromechanical Strain Gauge, 2016

Applications of MEMS energy harvesters

Automotive and aerospace applications

Innovate UK
Technology Strategy Board

McLaren
APPLIED TECHNOLOGIES

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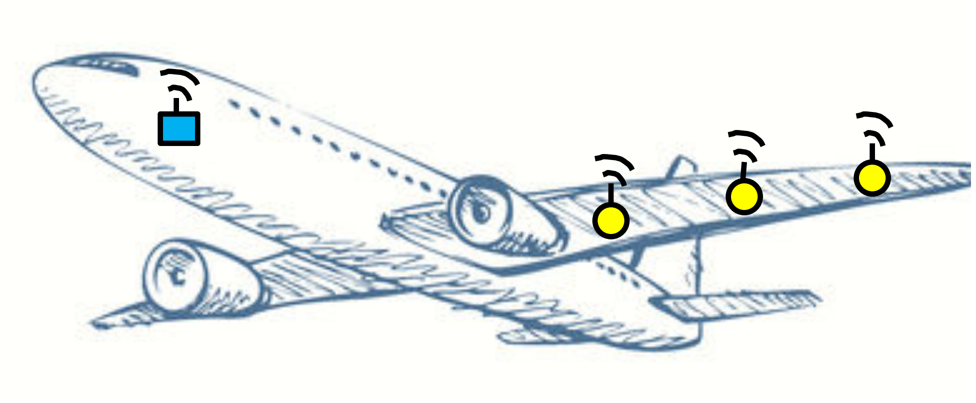
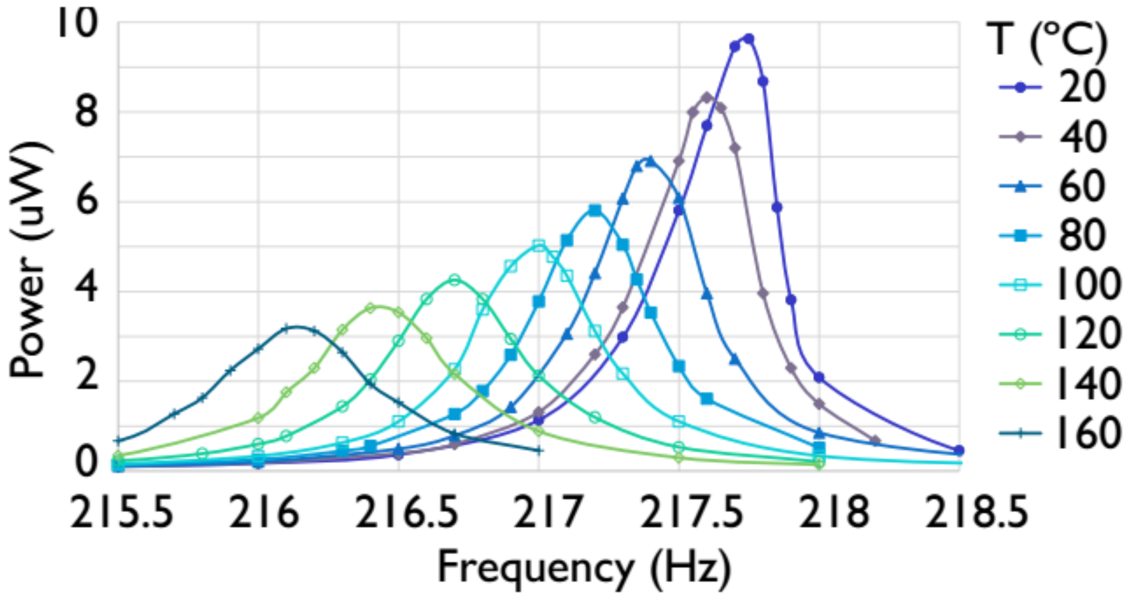
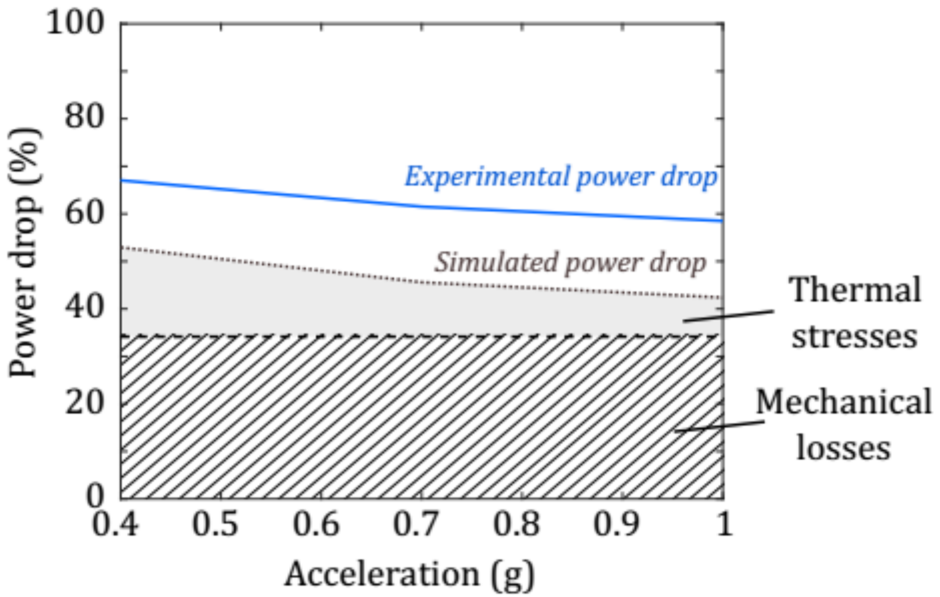


- deliver sufficient power to operate a miniature temperature and pressure monitoring modules
- Operate in small spaces, whilst under high vibration loading.
- Realisation of MEMS devices and wireless transmitters that can operate reliably at high temperatures (150°C and above)

Applications of MEMS energy harvesters

High temperature behaviour of piezoelectric cantilevers





- Experimental study show up to 70% power drop
- Thermal stresses and increased damping are the main causes behind power drop

E Arroyo, Y Jia, S Du, ST Chen and A Seshia, High temperature performance of a piezoelectric micro cantilever for vibration energy Harvesting, 2016

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