Imperial College London

Theme A: Adaptive, High Efficiency Microgenerators

Paul Mitcheson *et al*
Imperial College London
Holistic Workshop

holistic
energy harvesting

Adaptive?

Two degrees of freedom in a motion driven harvester:

- Tuning Frequency
  - Investigated here with variable reluctance to create a magnetic potential well

- Tuning Electrical Damping
  - Investigated with piezoelectric harvesters and suitable interface circuits

Theme A - Motivation

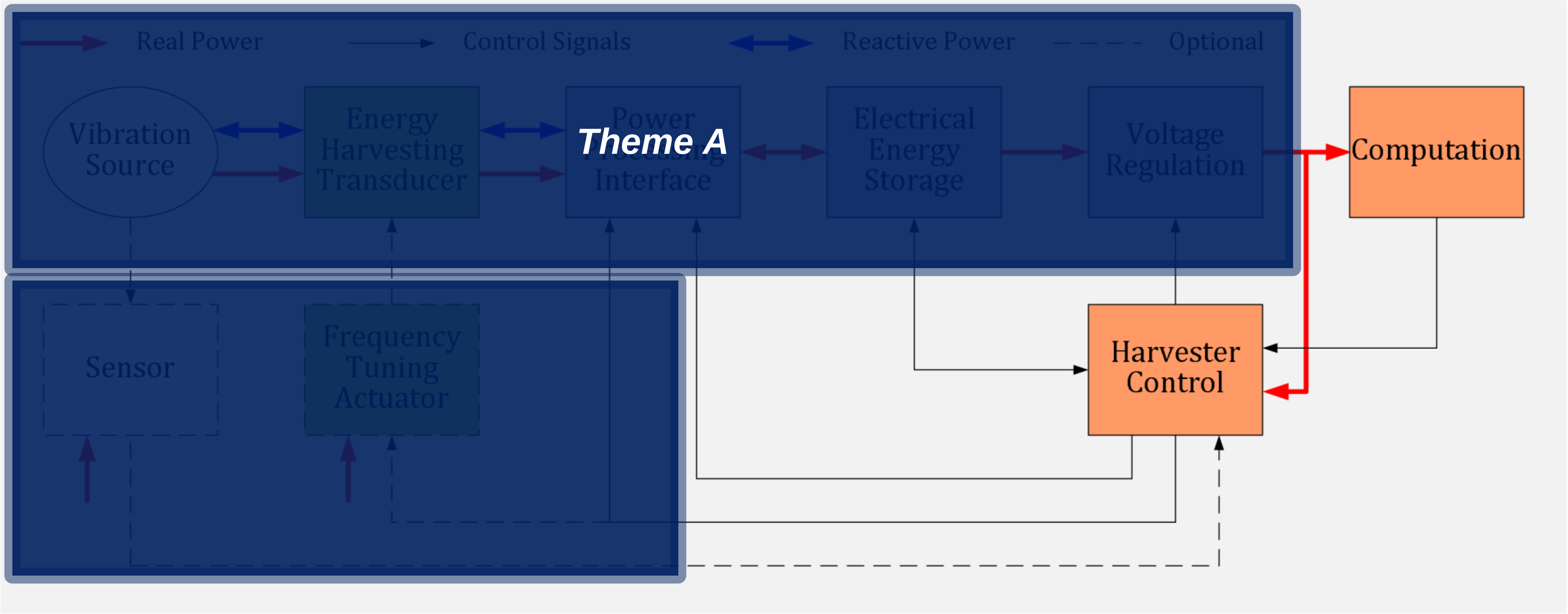
- Investigate harvesters that are useable in real world applications
- Time varying excitations (frequency and amplitude)
- Achieve high efficiency across the range
- Provide power in a useful form (not just maximise power dissipated in a resistor)

- There are two linking strands in theme A (each also links with the other themes):
  - Actuator-based tuning of an energy harvester
  - High efficiency power conversion electronics and low power control

Imperial College London

holistic energy harvesting

The System



Theme A has run throughout the project and involves Imperial, Bristol and Southampton

Outline

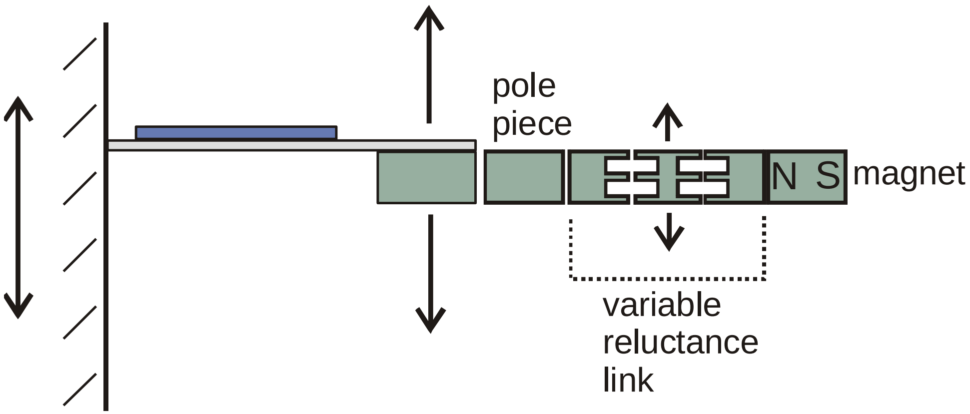
- Actuator based tuning
  - When resonant harvesters are detuned, they have poor performance
  - Need to modify resonant frequency with driving source
  - Must be done efficiently, with low power
  - Variable reluctance device as a MEMS solution
  - Macro-scale techniques

- Power electronic interface for piezoelectric harvesters
  - Low damping, low power
  - Techniques to increase damping (and power)
  - New circuit operating mode to achieve this
  - Simulations and prototype results

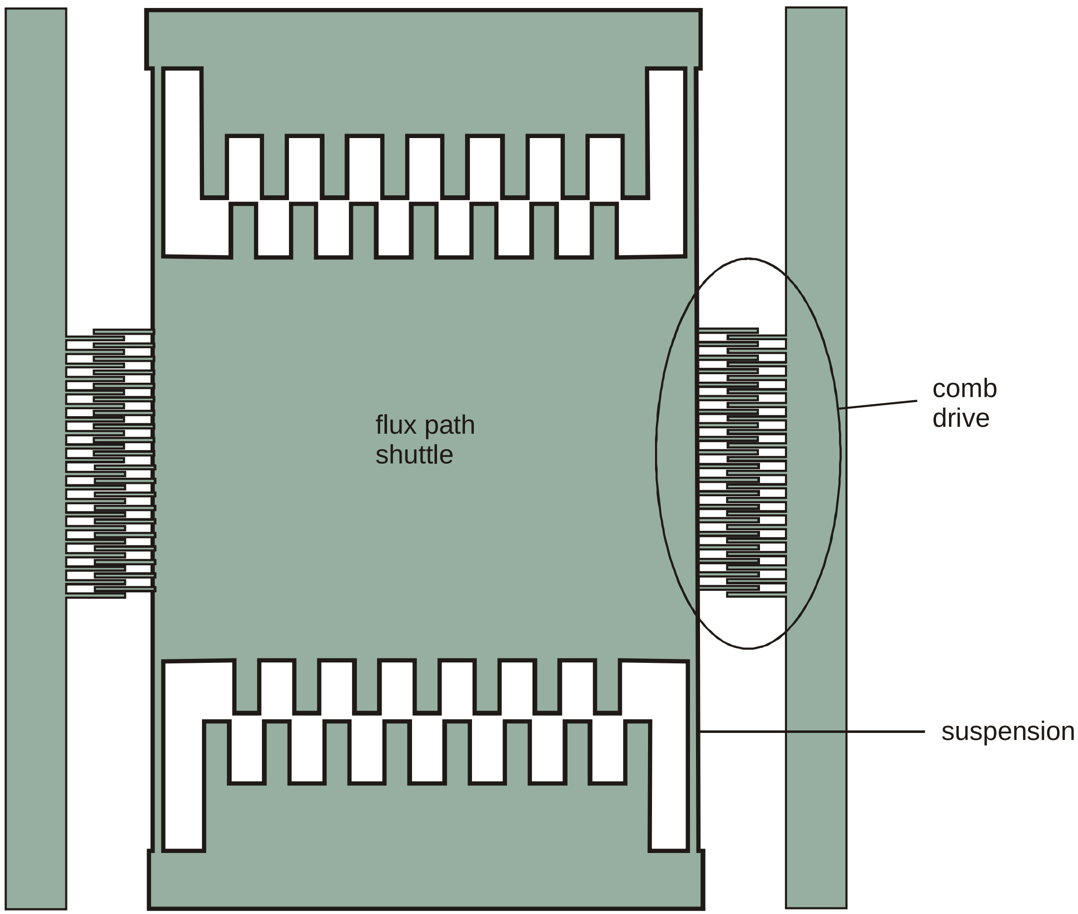
Actuator Based Tuning

Basic Concept

- Variable reluctance link
- Use permanent magnet, linked to oscillating proof mass by low reluctance path to pole piece
- Vary reluctance of this path by introducing a variable air gap
- Control this gap by MEMS electrostatic actuator



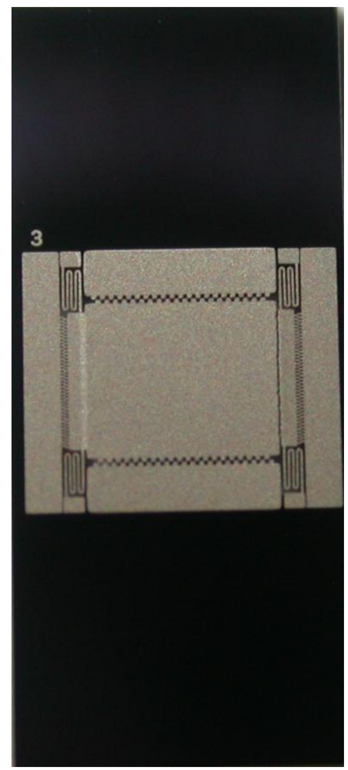
MEMS VRD



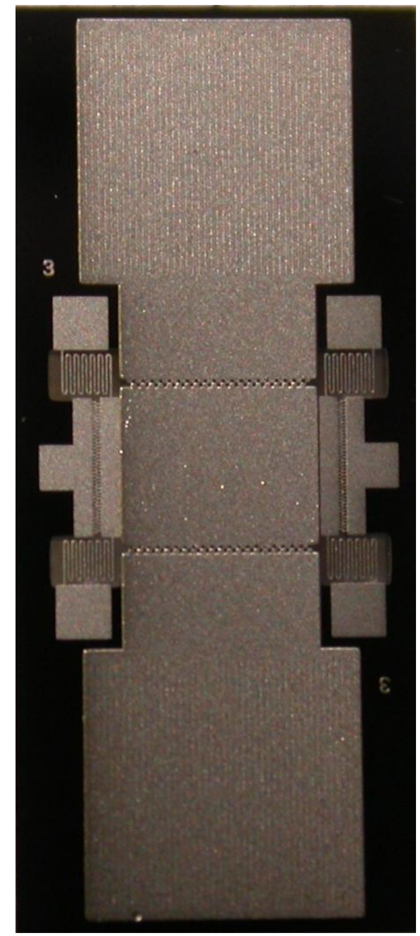
- Electrostatically actuated
- Alter magnetic reluctance between each end of the VRD

Picture of Fabricated MEMS VRD

Die size comparison

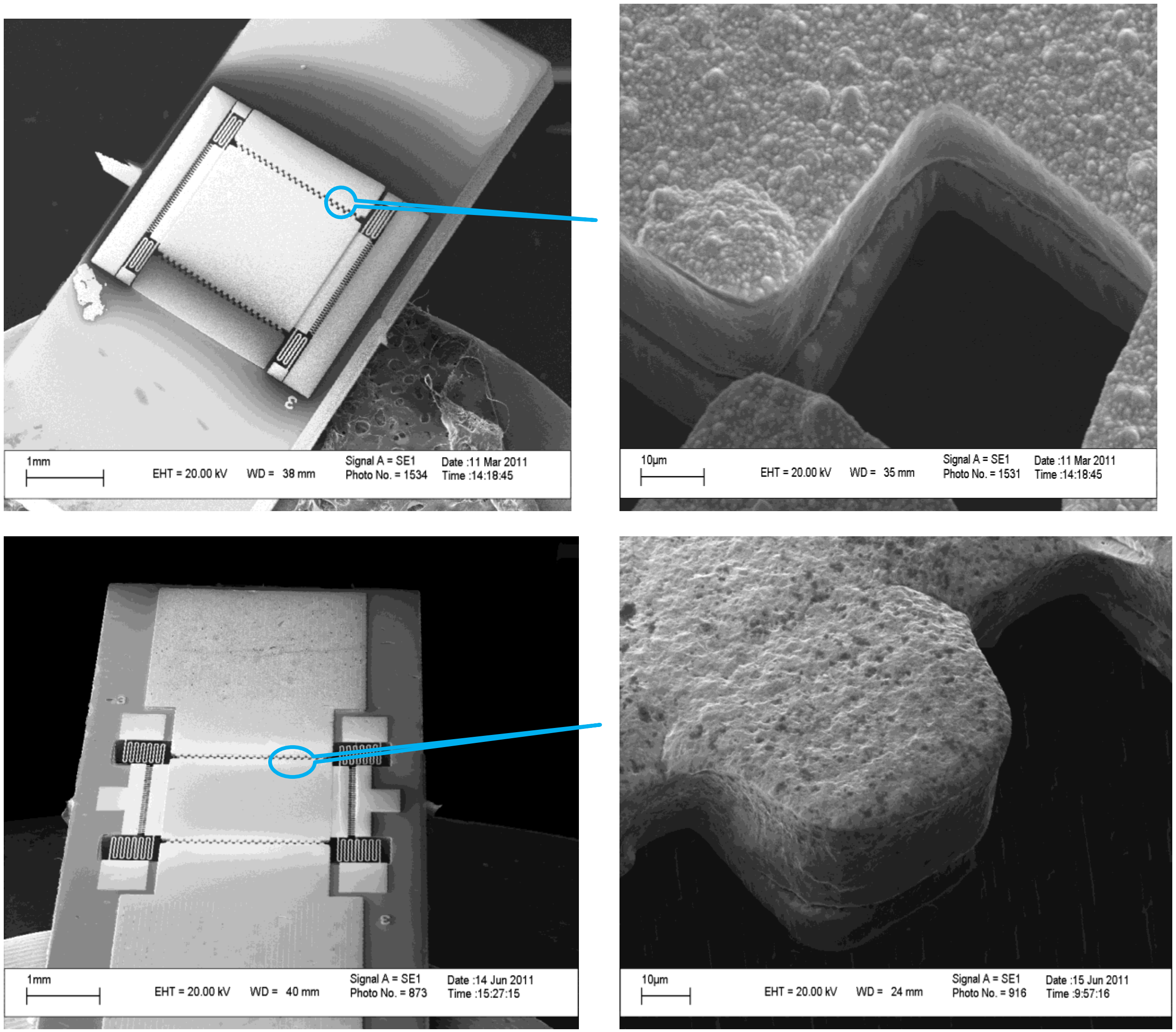


Previous fabricated die



Recent Fabricated Die

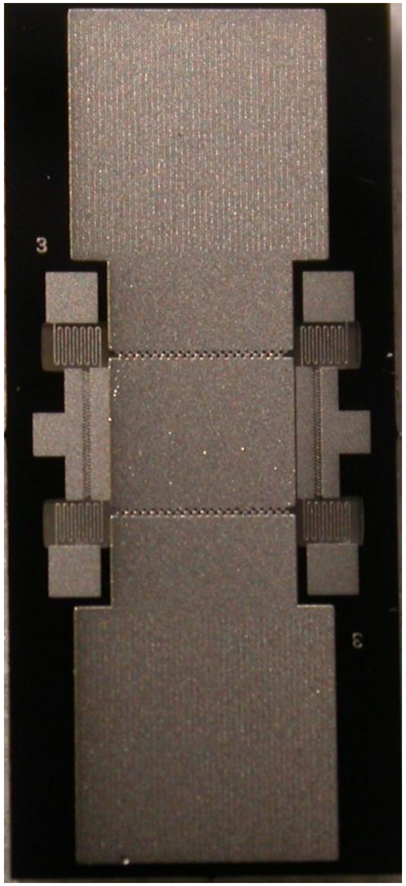
SEM Picture of the fabricated device



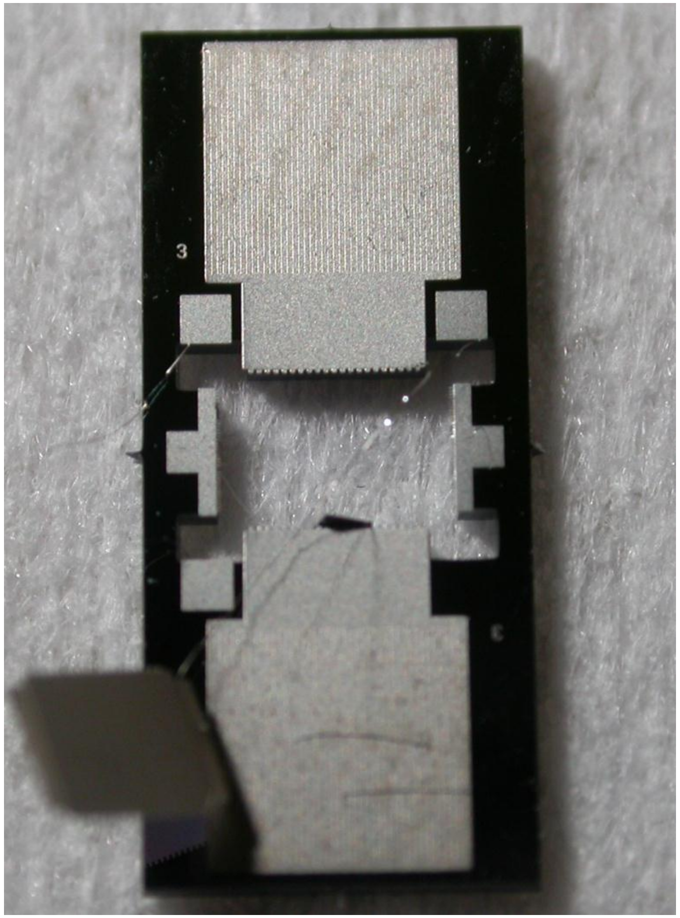
Difficulties with MEMS VRD

- Difficulty with attaching magnet to VRD without breaking die
- The magnetic properties of the plated Nickel are inferior to that of bulk material
- The changes in force achievable from the MEMS VRD were not sufficient to have significant impact on the larger electromagnetic harvester
- The electrostatic actuation was also overcome by electromagnetic pull-in but we demonstrated motion of the VRD using piezo actuation.
- Video has been running during the demo sessions

Manual Placement of Magnet

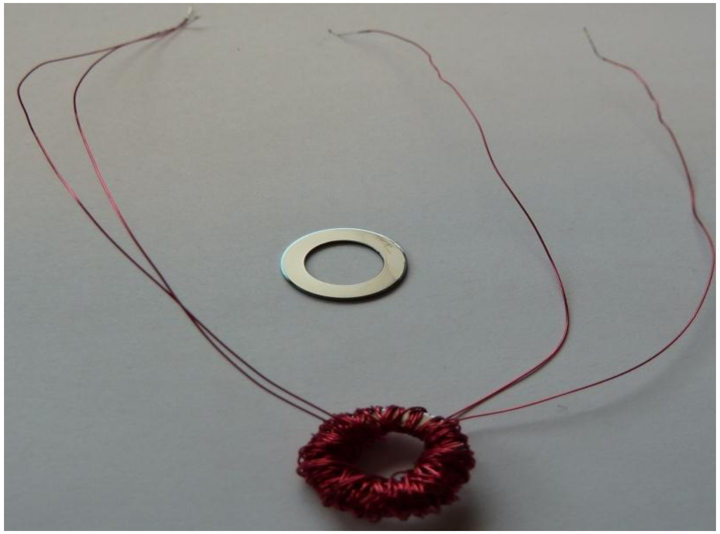


Before placing magnet on VRD



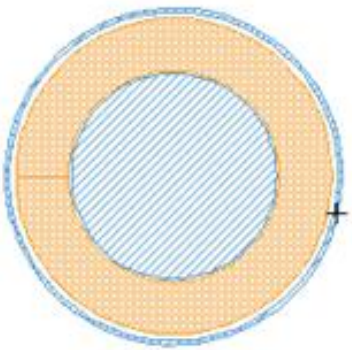
Movable part of VRD has pulled off due to magnetic force and broken the die

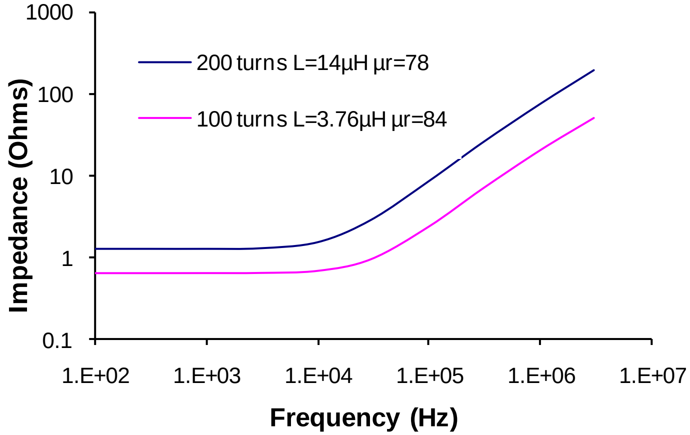
Characterisation Of electroplated Nickel



Inner diameter 8mm

Outer diameter 12.5mm





Permeability of the nickel layer is 80 from inductance measurement - the bulk value for nickel is about 600.

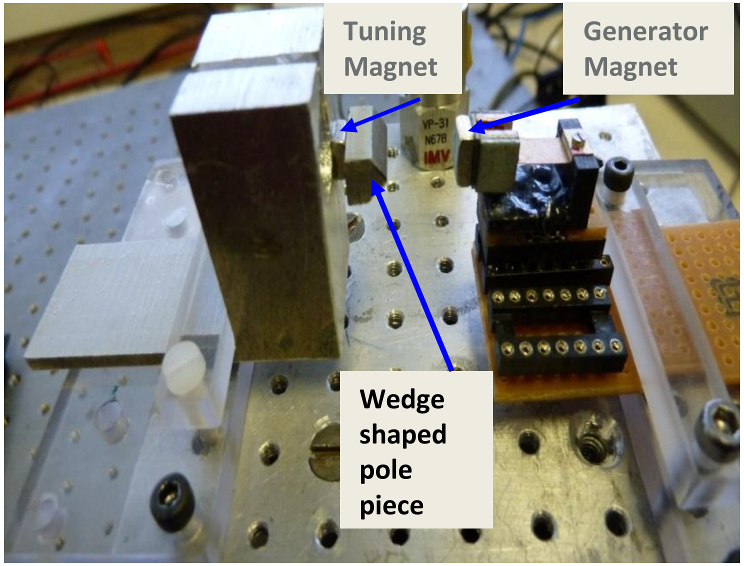
Through heat treatment, we have achieved at least a factor of 2 improvement

Macroscale Prototype

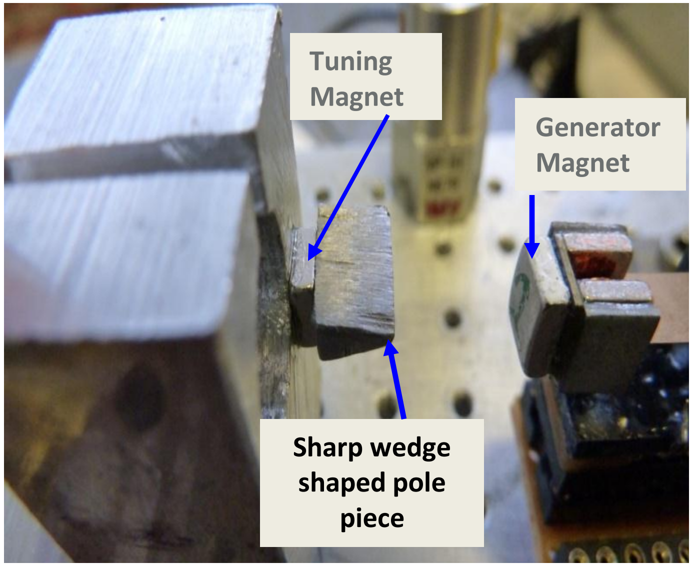
- In order to demonstrate the effect of a magnetic potential well on tuning, a macro scale prototype was created
- Significantly less force can be achieved to perform tuning by creating a magnetic potential well, rather than simply straining a cantilever
- Various experiments were conducted to measure the force required to tune, using shaped pole pieces
- The shaped pole pieces create the potential well, i.e. a kind of magnetic field spring

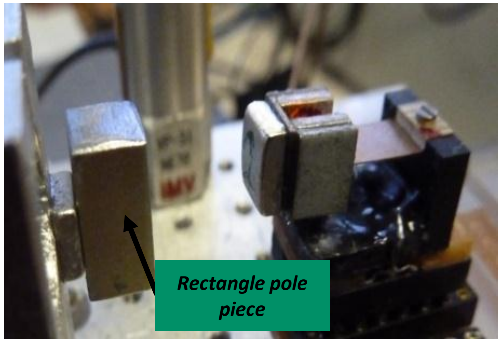
Magnetic tuning: Effect of field shape

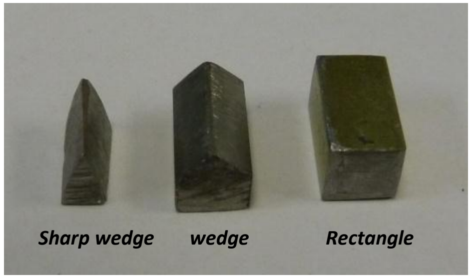
Test arrangement with sharp wedge shape pole piece



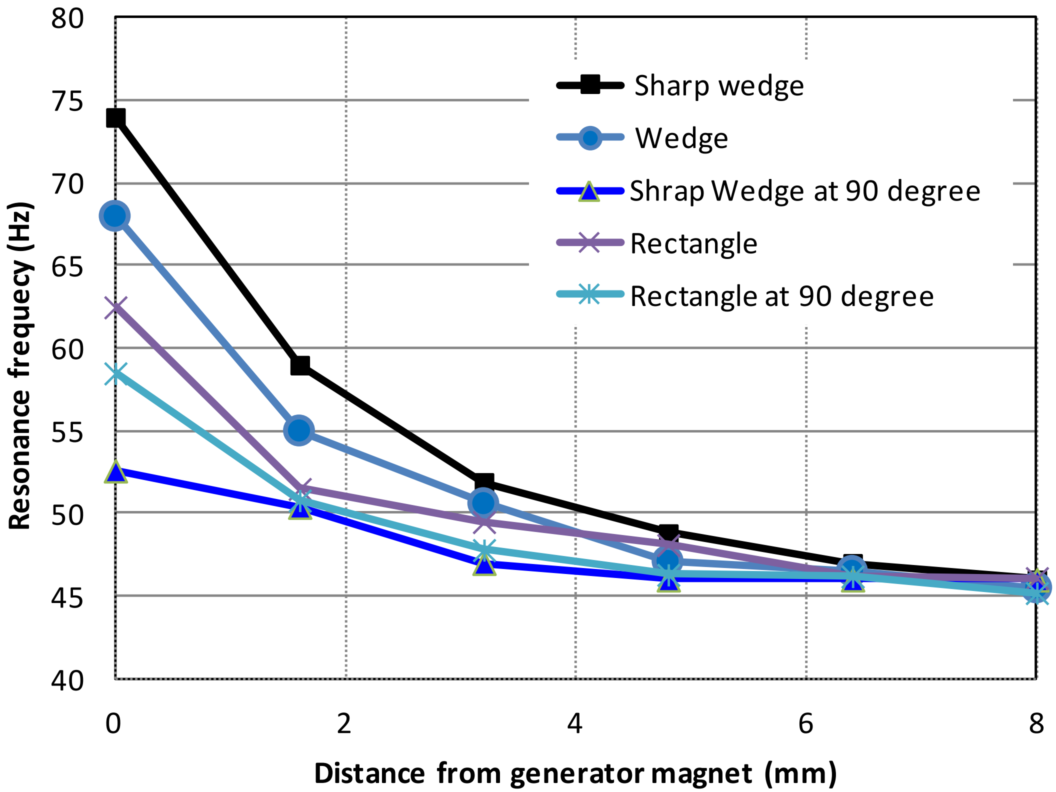
Test arrangement with wedge shape pole piece







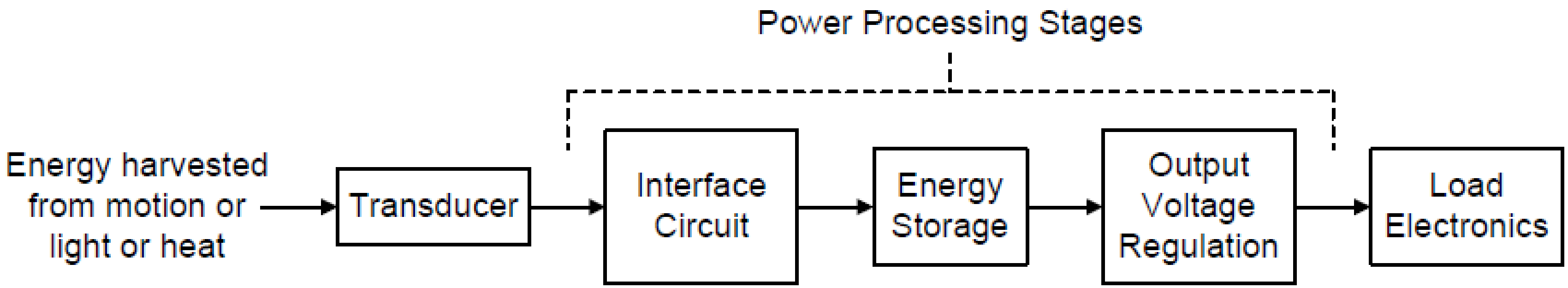
Shaped Pole Piece Tuning Results



- Significant improvement in tuning of +/- 20% using sharp wedge
- Shape has major impact in tuning range

Piezoelectric Interface Circuits

Motivation – the system



- The energy harvesting system must have a power processor stage between the transducer and storage element
- Bernard has already discussed this in detail for the electromagnetic harvester

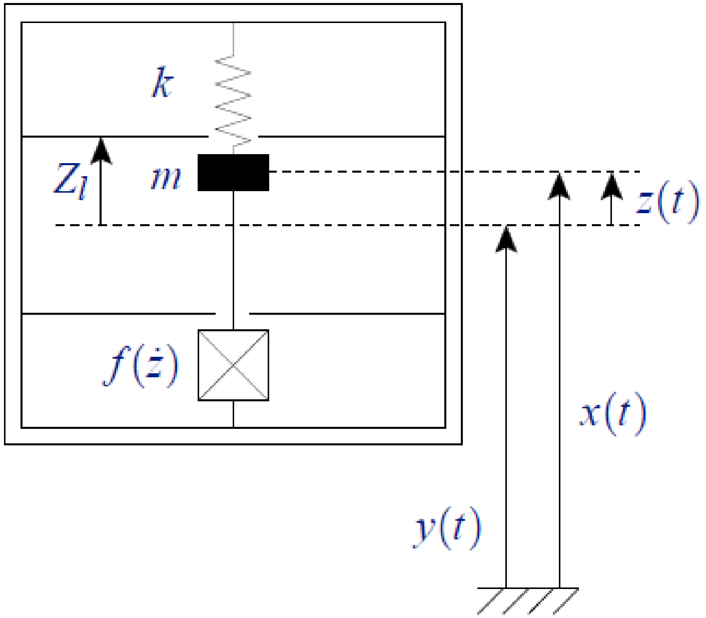
- We have been working on a new stream of work in the design of interface circuits for Southampton printed piezoelectric harvester materials

Piezo devices

- Attractive from power electronics perspective (reasonable trade-off between charge and voltage)
- Self-priming
- Can be expensive to obtain piezoelectric devices with high mechanical to electrical coupling
- Generally, high coupling is needed to achieve high power density

- Challenge: Can we compensate for the low piezo coupling of printed piezos using a power electronic interface?

Inertial Generators



- We need to set the value of the damper to maximise the generated power.
- The optimal electrical damping maximises the force-distance integral of the damper
- Too low, no force
- Too high, no displacement

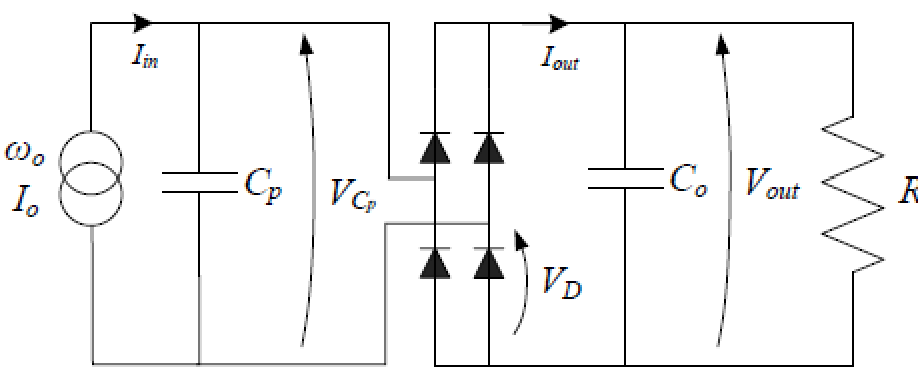
What value of damping can we achieve with a piezo? Can we reach the optimal?

Interface circuit must be able to rectify the piezo output

Piezoelectric Harvesters

Piezoelectric harvesters produce AC outputs

- Must have rectification
- May require step up or down depending on open circuit voltage of piezo.
- Simplest circuit we can think of is a full bridge rectifier:



Target is to achieve the optimal damping and rectify the signal simultaneously

- Can we achieve optimal damping (maximum power) with this interface?

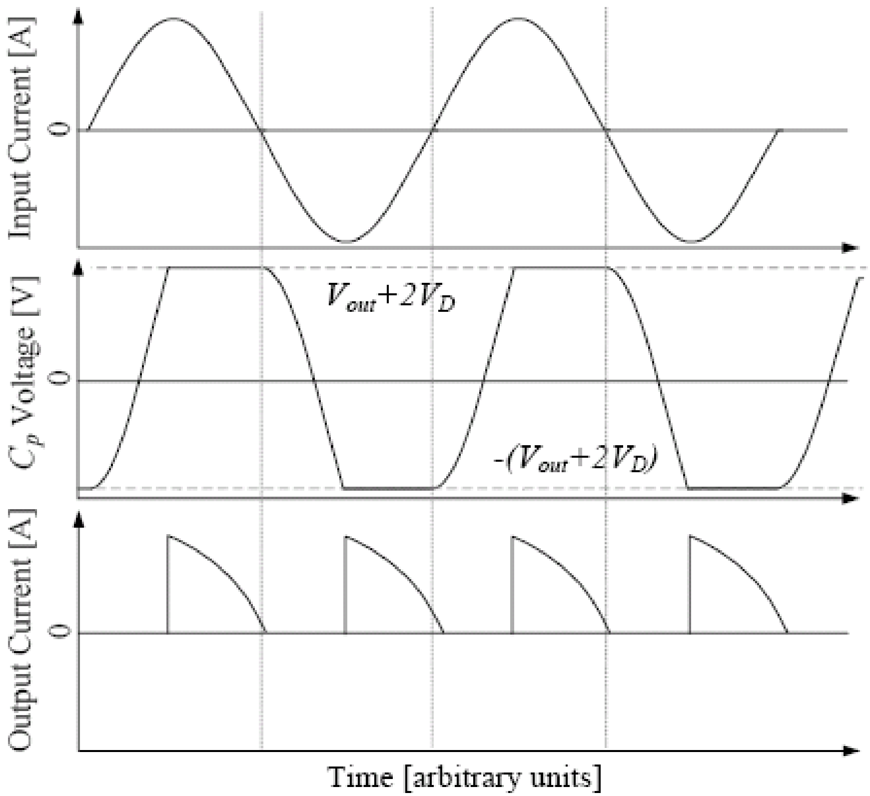
Imperial College London

holistic energy harvesting

Most of the time, not we cannot..

- If the harvester is weakly excited, voltages are too low to commutate diodes – no generation
- If the excitation is high, we need high damping to constrain the mass motion
- Calculate optimal energy by integrating charge wrt voltage, find optimal output voltage and calculate power:

$$P_{\max} = V_{po}^{\;2} f_o C_p$$

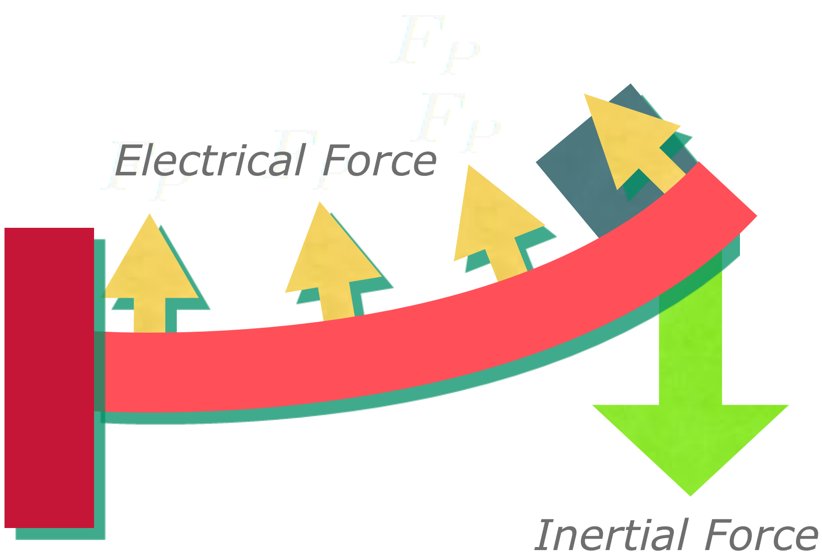


- Trade-off between force and time

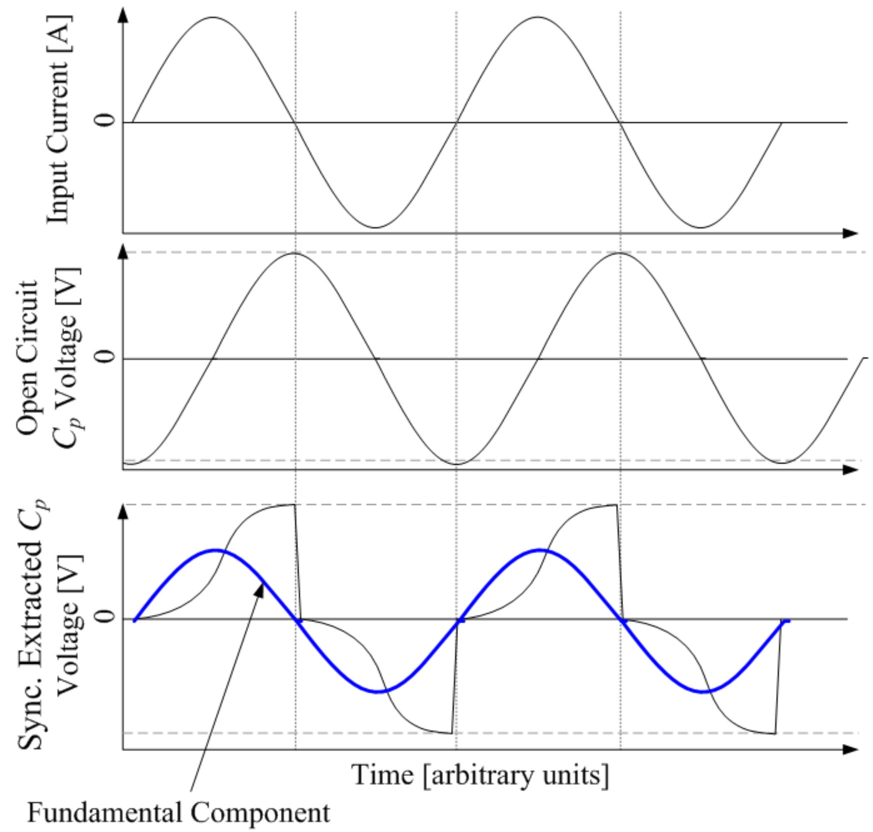
Increase the power (and damping) using switching techniques

Basic Concept for piezo switching circuits

We can think of the reason for the improvement in two ways:



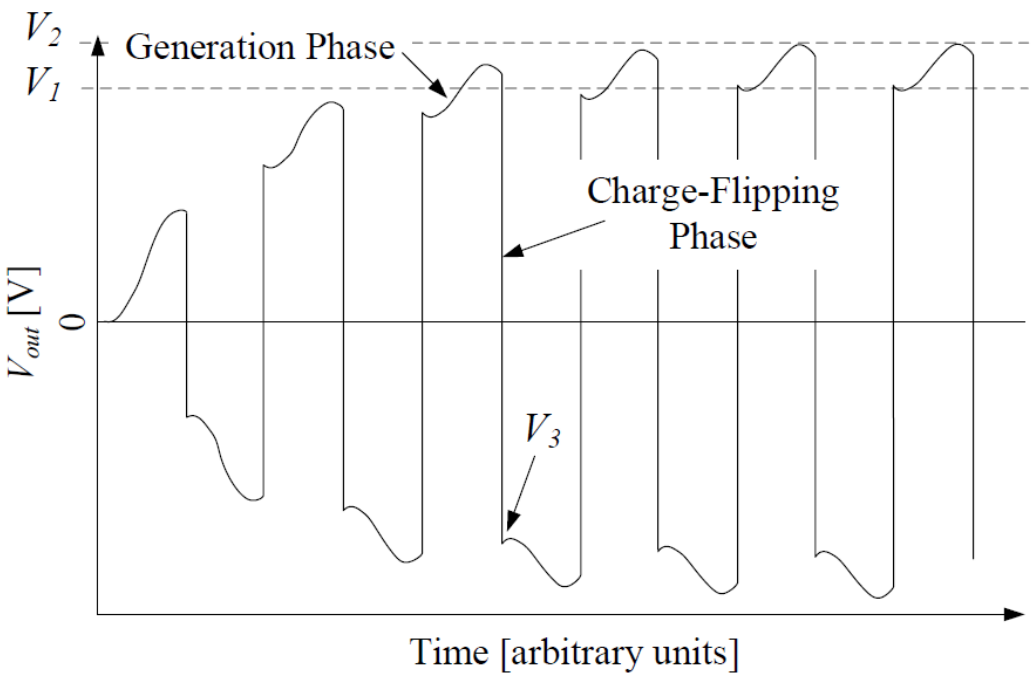
Increase in electrical damping

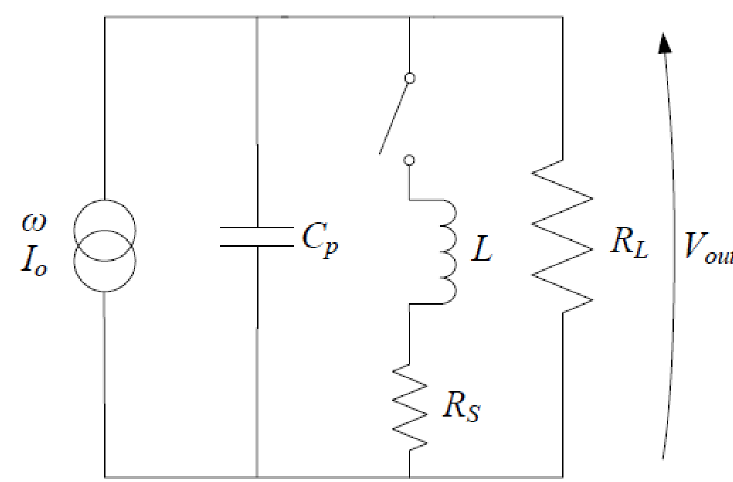


Improved power factor

Synchronous Switched Harvesting

Guyomar et al.



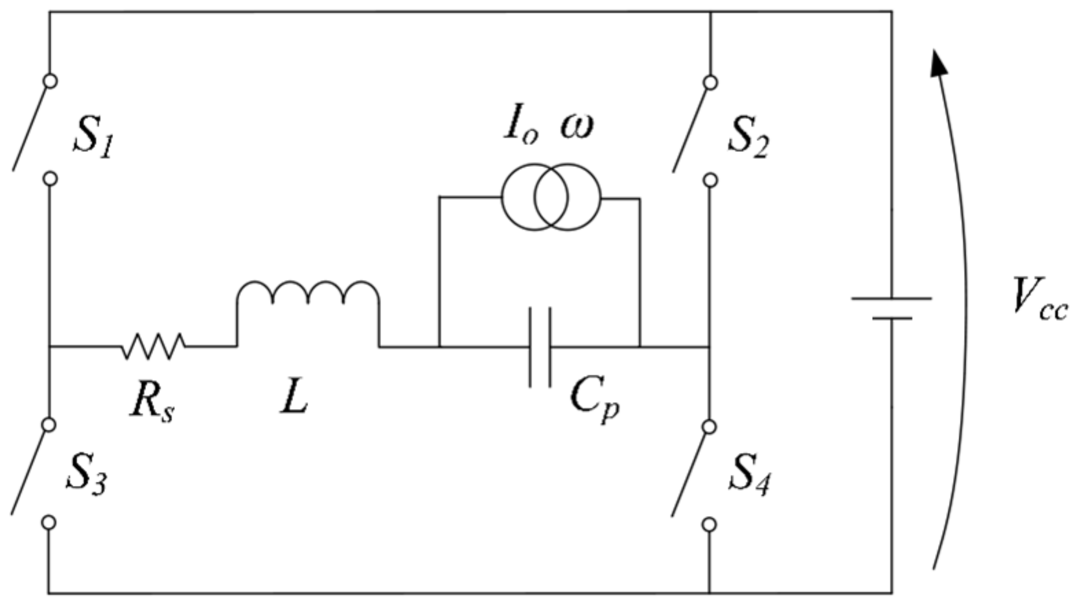


Often referred to as SSHI

- Charge on capacitor is resonantly flipped at voltage peaks to build piezo voltage
- Increases damping force and power

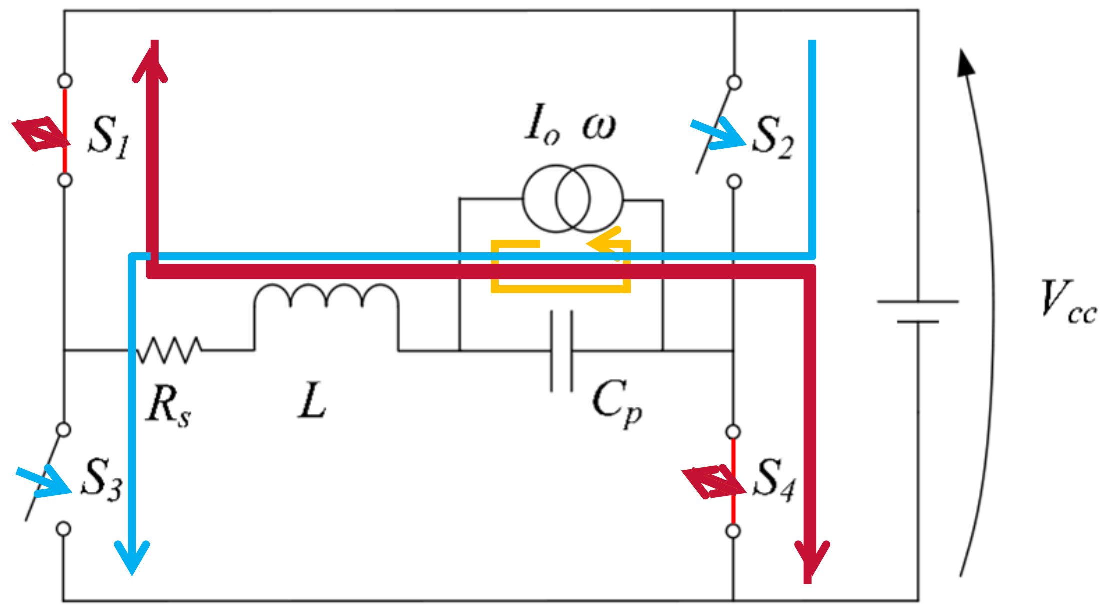
Single Supply Pre-biasing Circuit Overview

- Single source pre-bias circuit
- Source supplies pre-charge
- Generated energy returned to same source
- Can be made diode-less (with no free wheeling currents) if V_{CC} is optimally set



Let's see how it works…

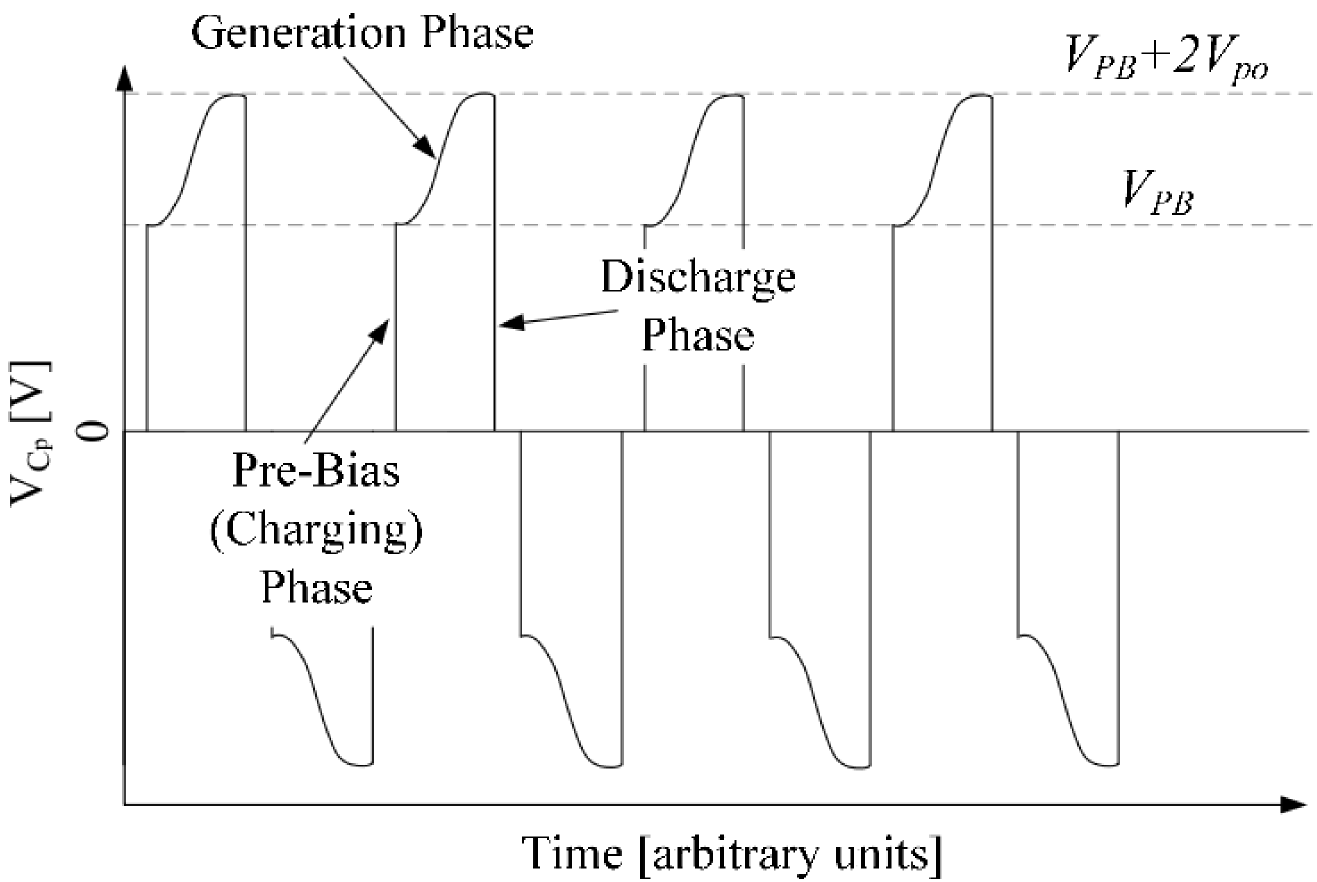
Single Supply Pre-biasing Circuit Operation



Imperial College London

holistic energy harvesting

Single Supply Pre-biasing Waveform



Operation similar to other synchronous circuits but charge "flipping" is in two stages

Power Output Formula

$$P_{\max} = V_{po}{}^{2} f_o C_p \left(\frac{8Q}{\pi} \right)$$

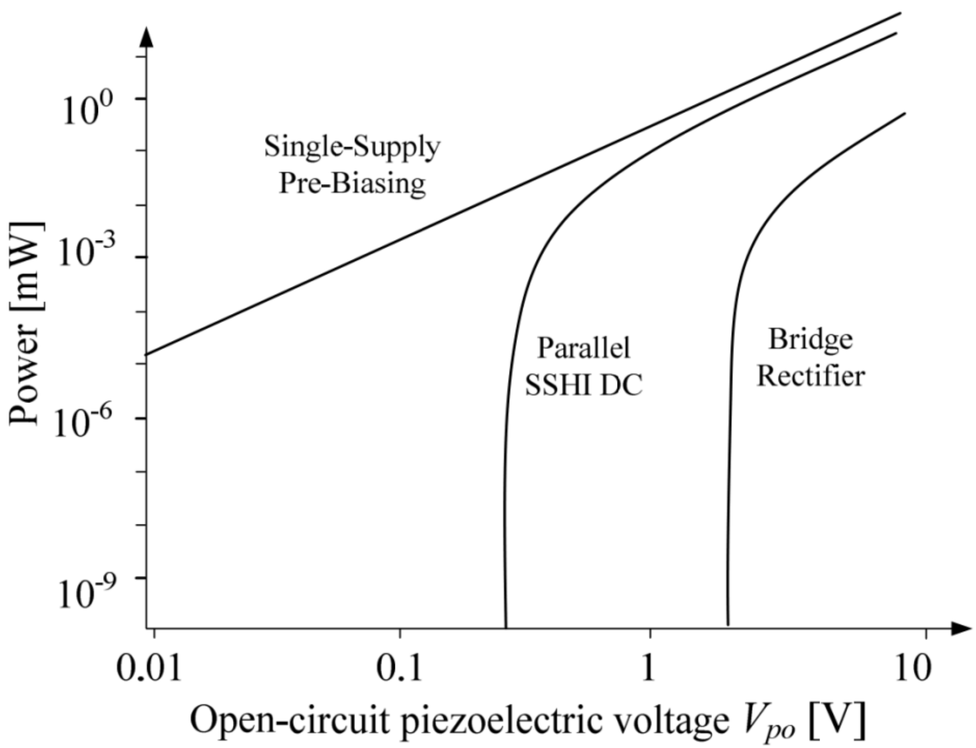
- V_{po} is the open circuit voltage of the piezo
- f_o is the mechanical excitation frequency
- Q is the quality factor of the resonant charging path
- C_p is the capacitance of the piezo

Comparison Versus Parallel SSHI Circuit

- Power output maximised for a given V_{out} and with $Q \to \infty$
- Single supply pre-biasing circuit 2x better than SSHI due to lack of charge flipping
- Diode drops prevent parallel SSHI and bridge rectifier from functioning

$$SSHI: P_{max} \approx V_{po}^2 f_0 C_p \left(\frac{4Q}{\pi}\right)$$

$$SSPB: P_{max} \approx V_{po}^2 f_0 C_p \left(\frac{8Q}{\pi}\right)$$



Plot for a Q of 5

Imperial College London

holistic energy harvesting

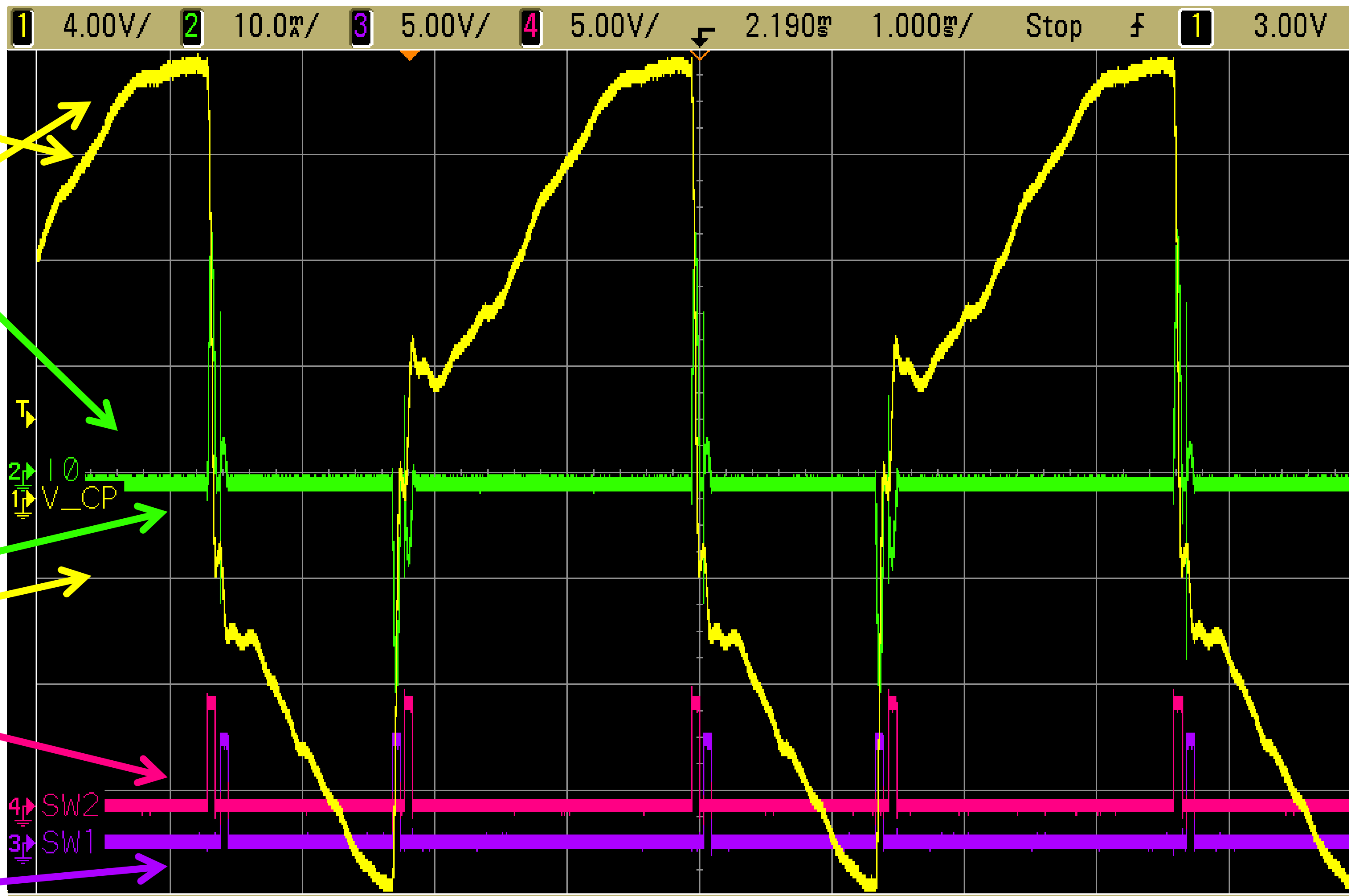
Experimental Results

Pre-Biasing Circuit Piezoelectric Voltage Waveform

Zoom in of Voltage Waveform

Piezoelectric voltage

Piezoelectric current



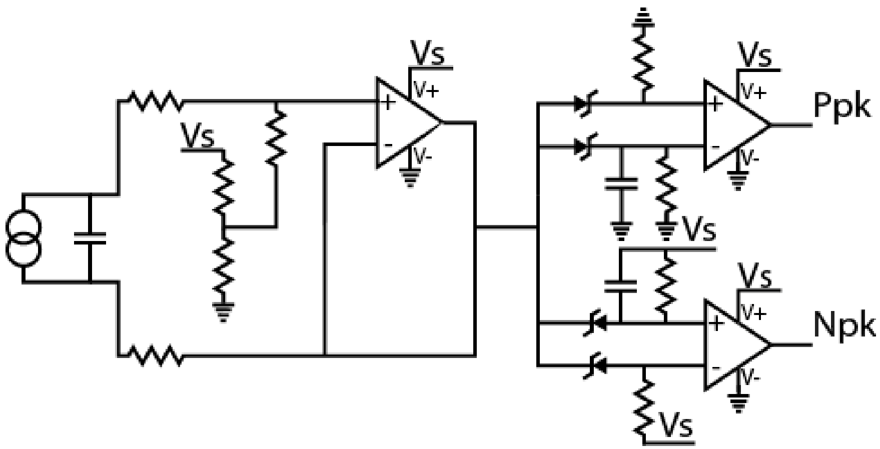
Piezoelectric current

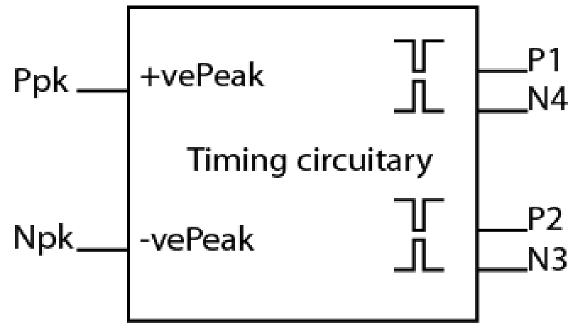
Piezoelectric voltage

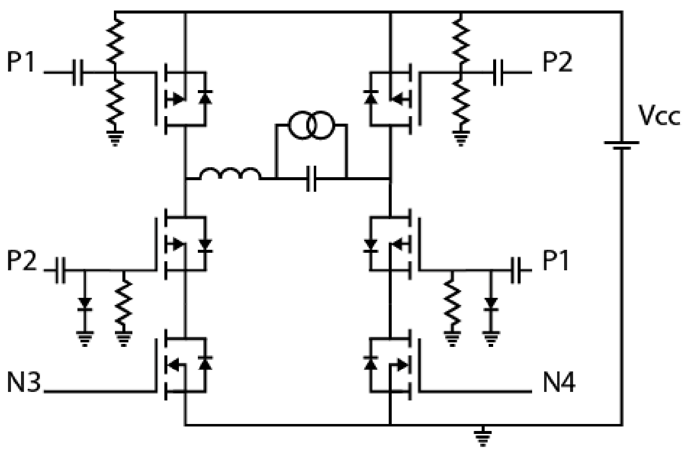
Switch 2 & 3 timing signal

Switch 1 & 4 timing signal

Recent improved Implementation





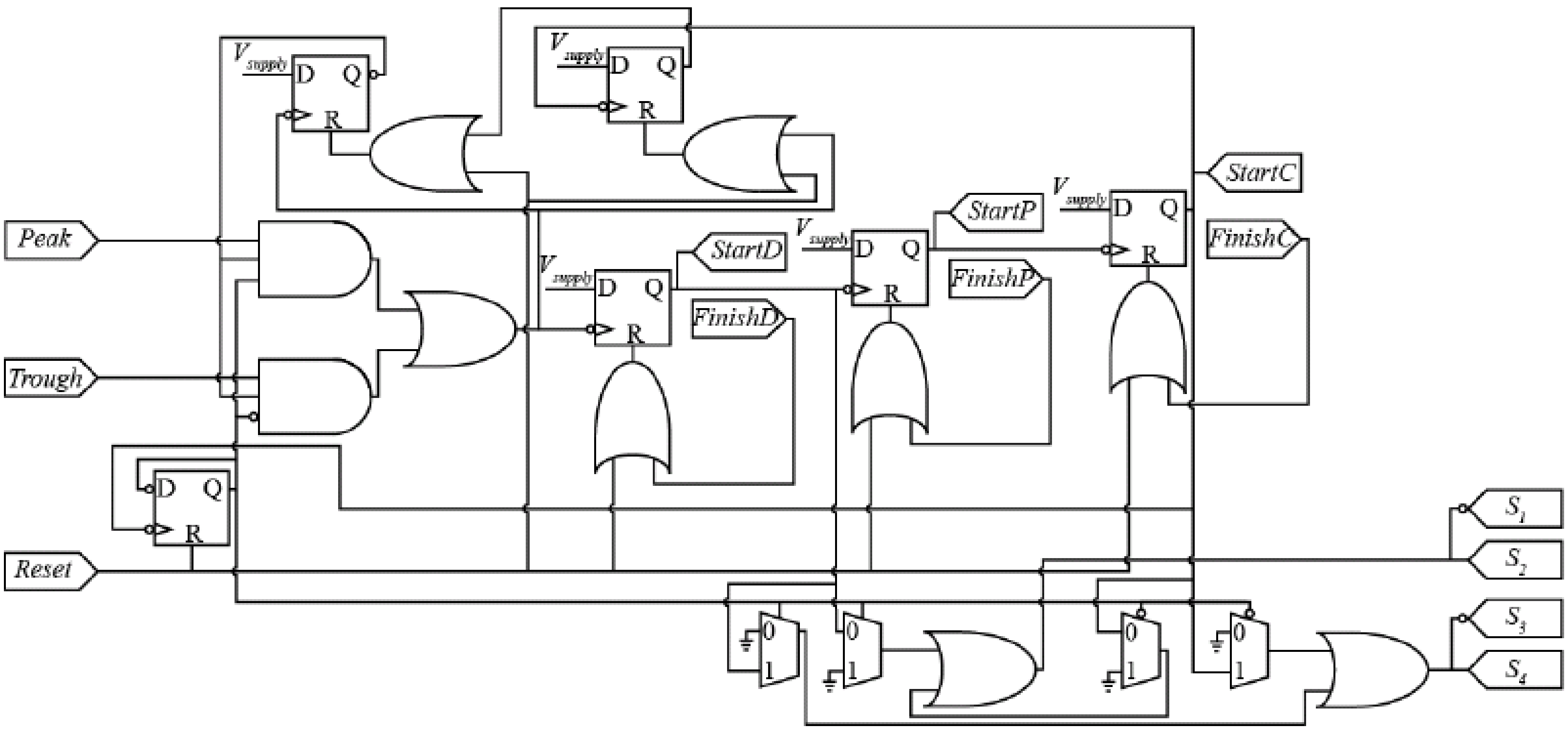


- Implemented using discrete low-power components
- Note the H-bridge bi-directional blocking
- Power Consumption of 40 μW (and reducing)

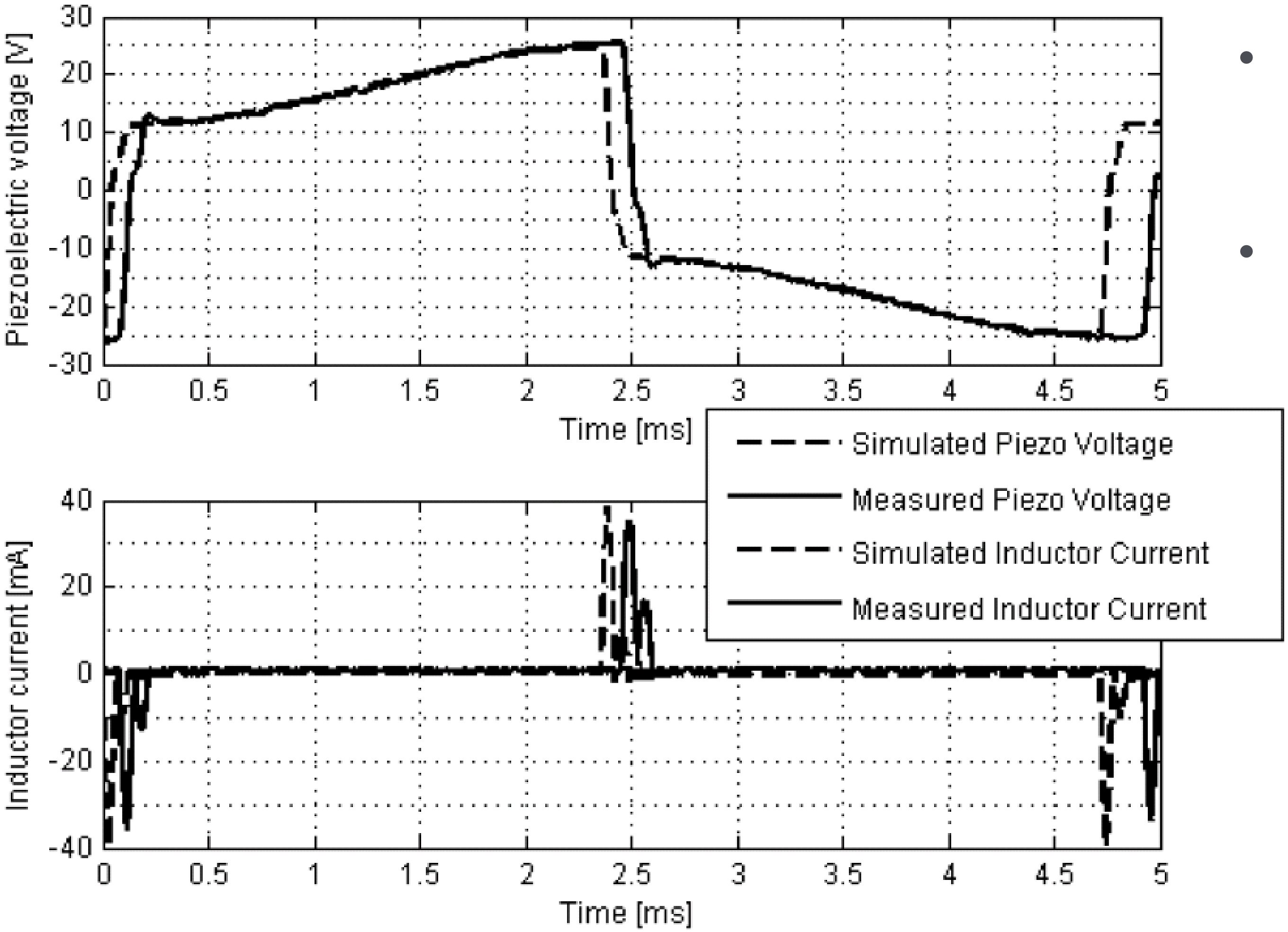
Low Power Control and timing...

Done on low power Igloo Nano FPGA

Relatively simple – just switch time and sequencing

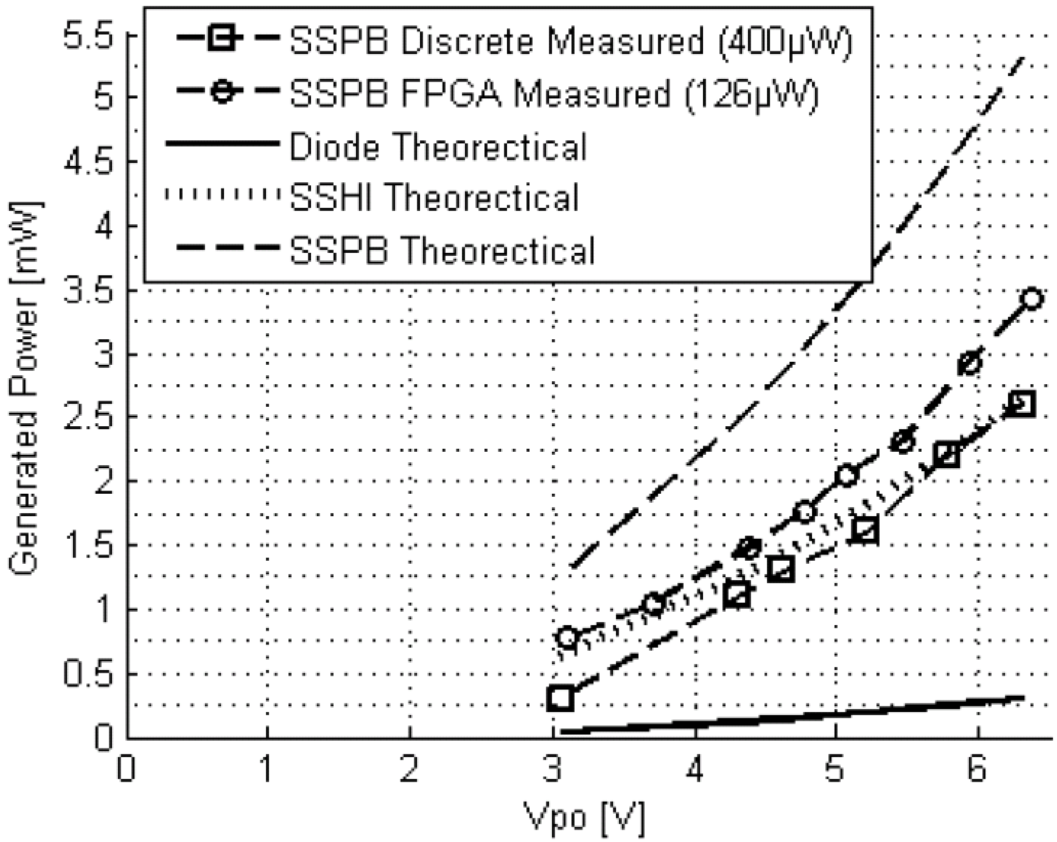


Improved Waveforms



- Reduced artefact from circuit parasitics
- High quality waveforms approaching ideal

Power Comparison



- Vast improvement over bridge rectifier
- SSPB practical implementation is better than the best possible perfoamance of SSHI (even allowing for zero control overhead on SSHI)

For a review on all types of piezo interface circuits:

Dicken J, Mitcheson PD, Stoianov I, Yeatman, EM, ***Power-Extraction Circuits for Piezoelectric Energy Harvesters in Miniature and Low-Power Applications****, IEEE Transactions on Power Electronics, 2012, Vol:27, Pages:4514-4529, ISSN:0885-8993*

Pulling Together the System

What force do we need?

The force on the piezo is:

$$F = k_0 Z + \frac{\Gamma}{C_0} q$$

First term is a spring term, second is constant if the piezo is open circuit
This is a Coulomb force.

Optimal value of a Coulomb force for a harvester is:

$$F_{opt} = \frac{\pi}{4} m \cdot A_{input}$$

Linking Damping to Piezo Voltages

What force do we need?

$$V_{PB} = \left(-\frac{\pi}{4} m \cdot A_{input} + \frac{\Gamma^2 Z_l}{C_0} \right) \frac{1}{\Gamma}$$

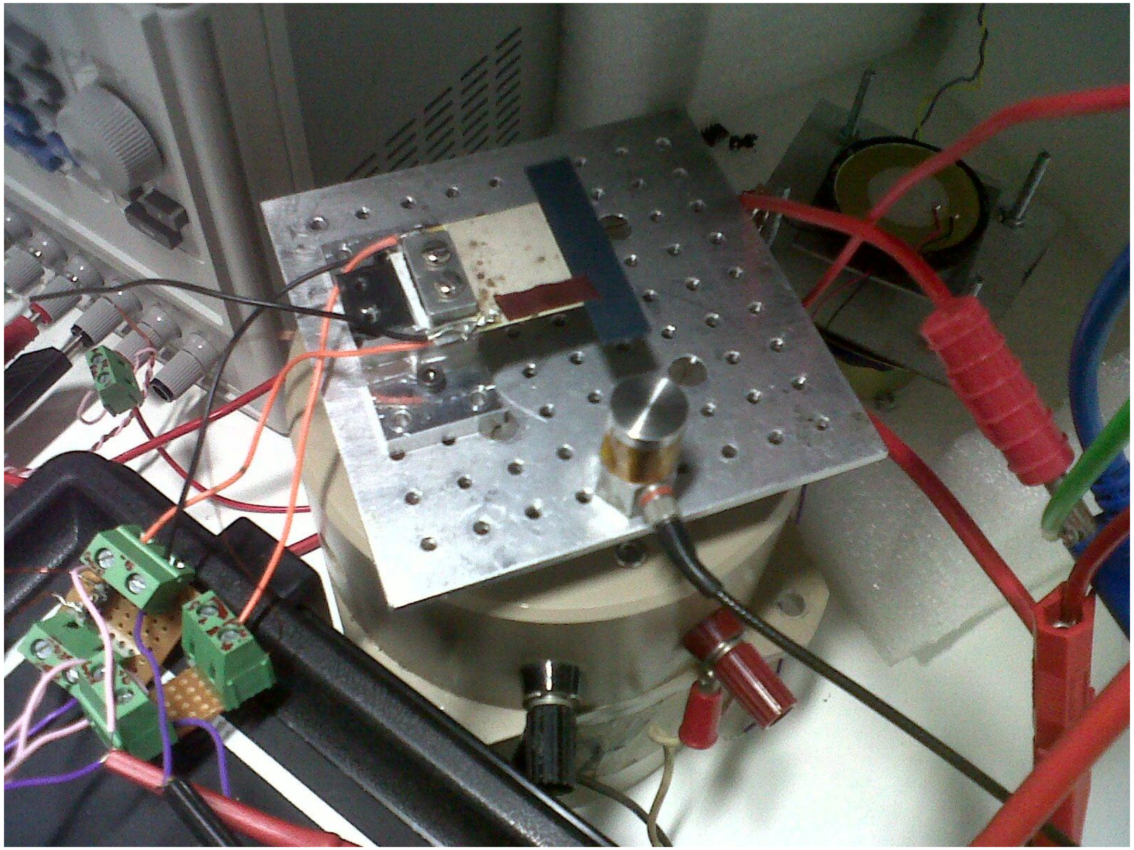
This system allows:

- Optimised mechanical coupling
- Increase coupling for marterials with low transduction factors
- Rectify the power inherently as part of the system

For more detailed derivation, see:

Miller LM, Mitcheson PD, Halvorsen E, et al, ***Coulomb-damped resonant generators using piezoelectric transduction****, Applied Physics Letters, 2012, Vol:100, ISSN:0003-6951*

Imperial Circuit, Southampton Generator



Around 100µW was generated with the SPB interface. Power with a bridge rectifier was not detectable using our power meter – which has a sensitivity to 10µW.

Conclusions

- Significant progress on MEMS VRD fabrication
- Work underway to improve Nickel properties
- Shaped pole pieces and magnetic potential well used to improve tuning range and reduce actuator tuning force

- New piezoelectric interface circuit developed which has a performance of twice other known techniques
- Good agreement between results and theory
- Low power control circuit developed (asynchronous logic, recommended by Newcastle)
- Results from connection of Southampton piezo harvester are very encouraging

Acknowledgements

Work supported by EPSRC

Grant number EP/G070180/1

“Next Generation Energy-Harvesting Electronics: Holistic Approach”

2013 PowerMEMS

United Kingdom, Dec 3rd – 6th 2013

PowerMEMS School Dec 2nd – 3rd

More information:
http://www.powermems2013.org

Join our Facebook Page:
http://www.facebook.com/PowerMEMS2013