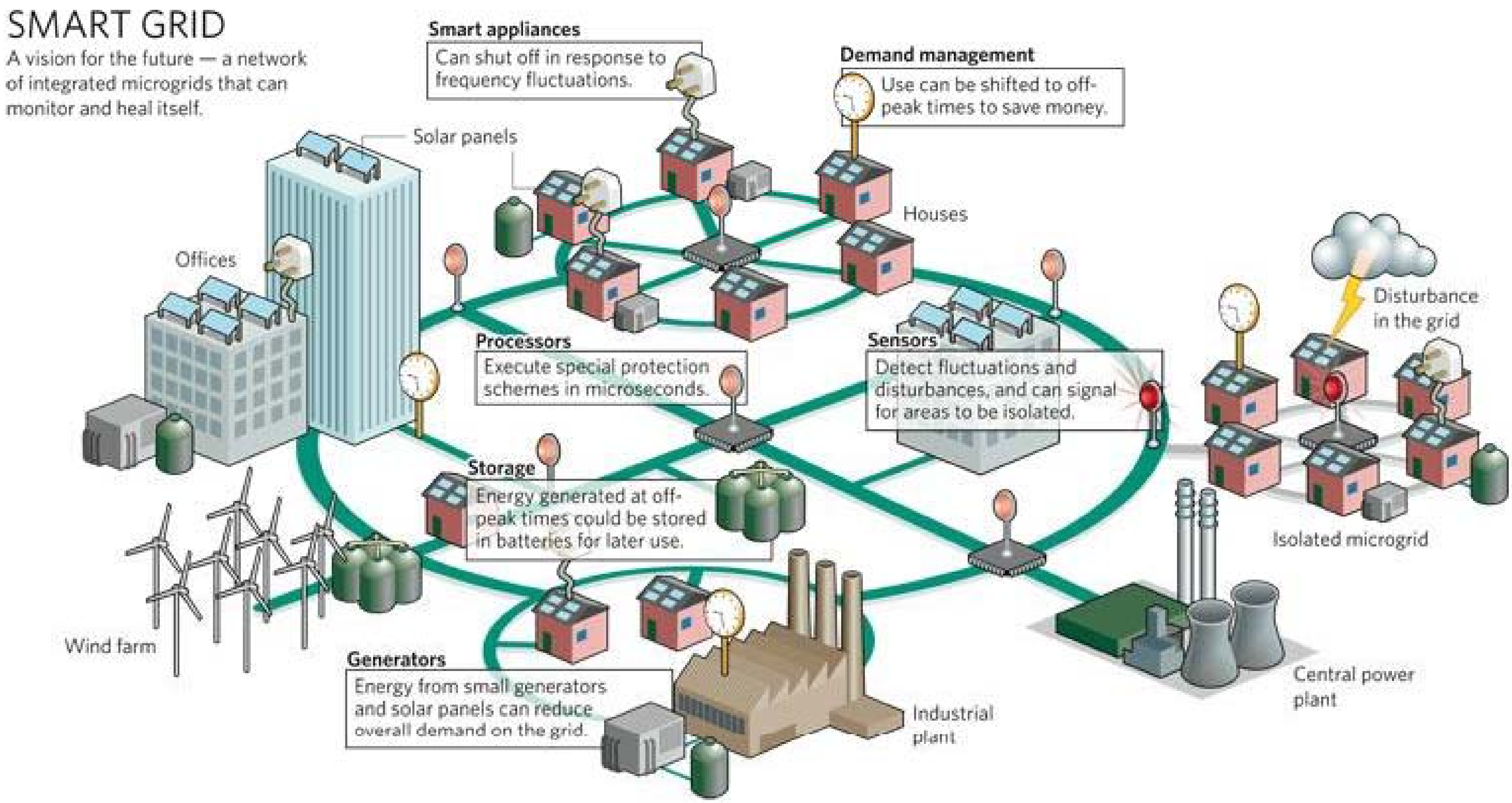
The New "Smarter" Grid



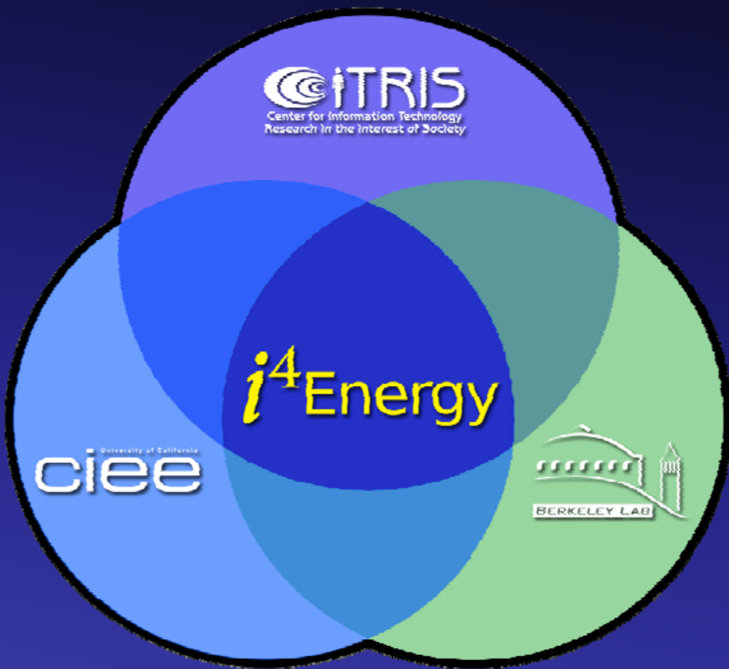
Consumer Energy Report

Next 10 years will see $170Billion invested in the Smart Grid, Half of which is in smart sensors and devices – Smart Grid News

i^4Energy Center

At the intersection of energy and information technology

Innovation – Intelligence – Integration – Information



- *i^4Energy* encompasses the research of CITRIS, BSAC, BWRC, BMI, California Institute for Energy and Environment, and the Lawrence Berkeley National Laboratory.






Scope of Current Research Projects

- Enabling Technologies Development
  - Applications in demand response, electricity distribution, and building energy efficiency

- Smart-Grid Research, Development, and Demonstration
  - Renewables integration strategies, residential gateway reference design, and information exchange R&D

Integration Platforms: Towards the Wafer Scale

- Alic Chen, WeiWah Chan , Rick Doering, Giovanni Gonzales, Christine Ho, Mervin John, Jay Kaist,, Deepa Maden, Michael Mark, Lindsay Miller, Peter Minor, Christopher Sherman, Mike Seidel, Joe Wang, Andrew Waterbury, Lee Weinstein, Richard Xu, Fred Burghardt, Domenico Caramagno, Dan Chapman, Dr. Igor Paprotny, Dr. Yiping Zhu, Prof. Jan Rabaey, Prof. Jim Evans, Prof. Dick White, and Prof. Paul Wright (Profs. David Auslander Duncan Callaway, David Culler and many many other students)

- Lower Power Radios – Michael Mark and Jan Rabaey
  - Recent low-power designs
- Electrical Current and Voltage sensing – Dick White
  - Demonstration from breaker panels in Etcheverry Hall and this Building (SDH)
- Thermal Electric and Vibration based Energy Scavenging – Alic Chen and Lindsay Miller
  - Devices and integration with storage
- Battery Storage – Jim Evans
  - Integration with scavenging and storage
- A related Test Bed project in Sutardja Dai Hall (SDH) – Domenico Caramagno
  - Results on sub-metering and large opportunities for installing ETD sensors

Past, Present and Future

- The radios we built …

  … consume 1 to 2 orders of magnitude less power than commercial radios

  …enable small wireless sensing nodes powered purely by energy scavenging
- In progress: Integration of radios with energy harvesting/storage and power conditioning
- Next step: Interfacing with sensors while improving performance and level of integration

For a leaf node*, the average power can be given by:

$$P_{avg} = \frac{\frac{bit}{bsp} \cdot P_{tx} + \left(T - \frac{bit}{bsp} \right) \cdot P_{sleep}}{T}$$

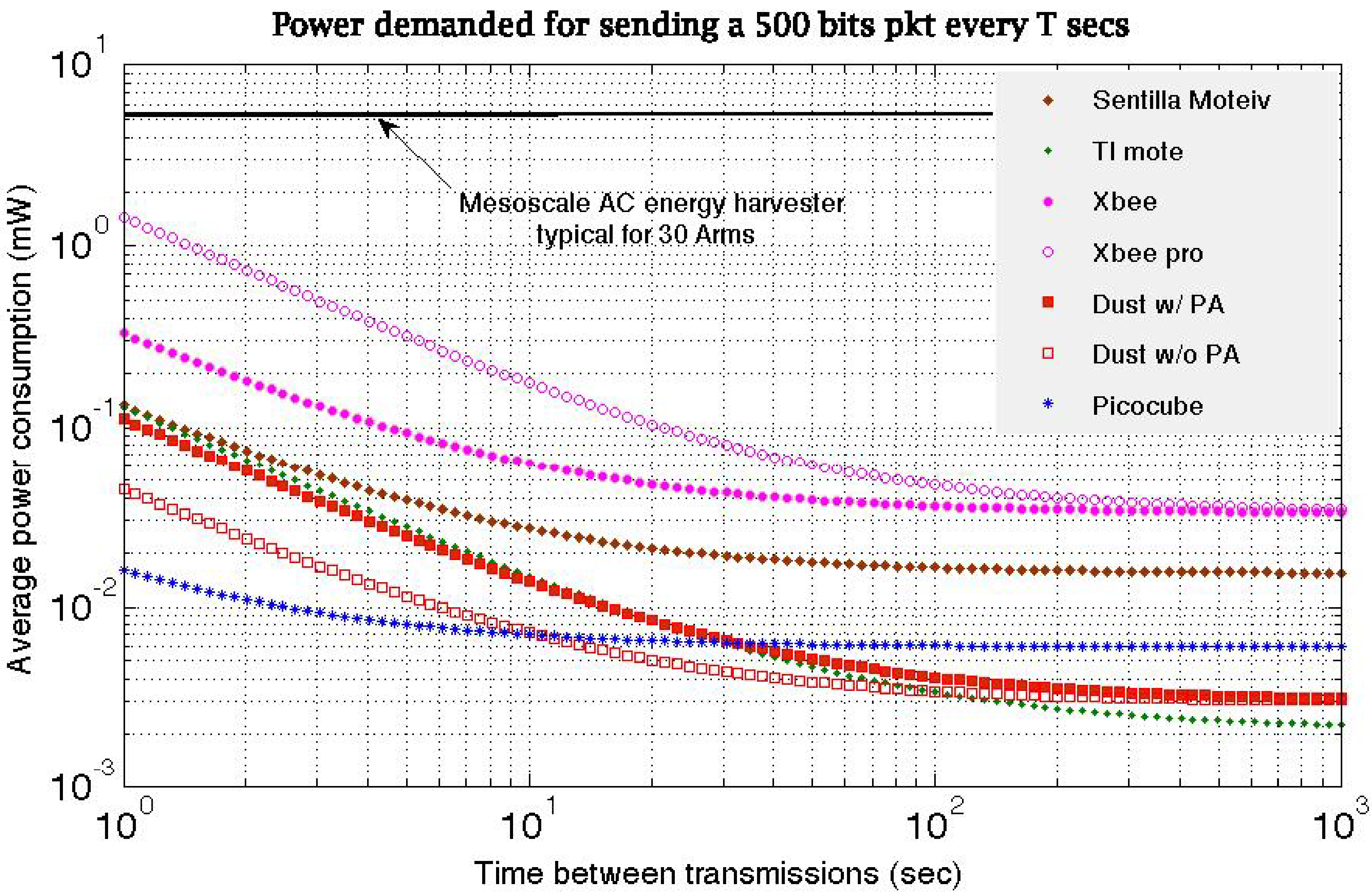
* A leaf node only does the job of sending data from its ADC. It does not serve as a router for other nodes as those used in multi-hop applications. TX current dominates for a leaf node.

bit: is the size of the package to be sent

bps : bit rate (bit per second)

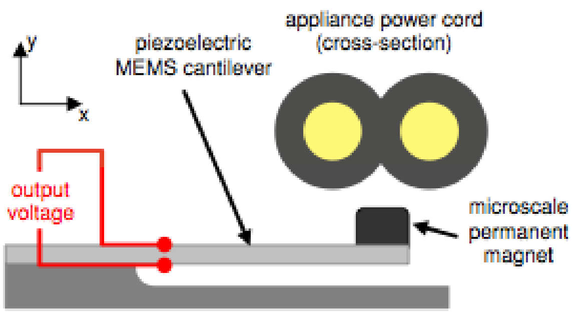
T : is the time interval between each measurement

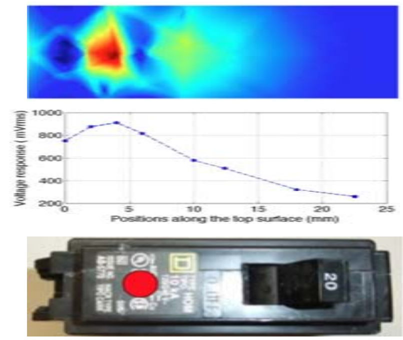
P_{avg} is equivalent to the power needed from a energy scavenger

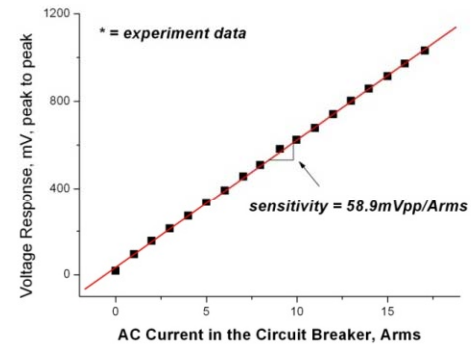


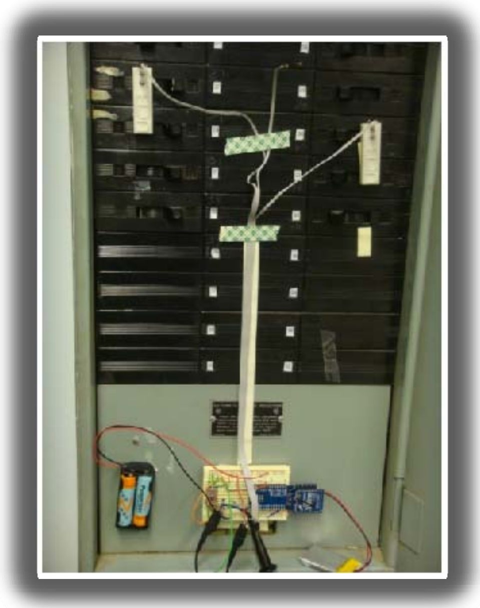
Sensors: Wirelessly enabled electrical current sensor nodes on circuit breaker panels

Working principle:

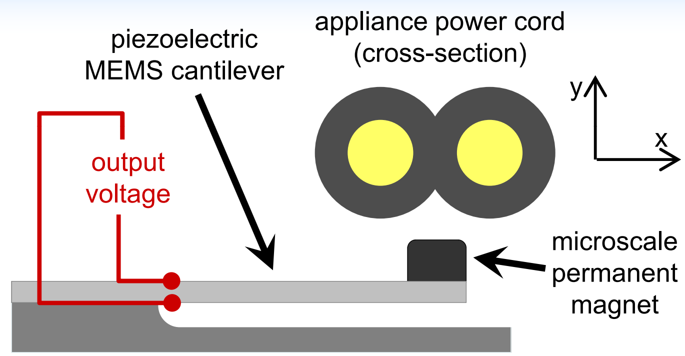


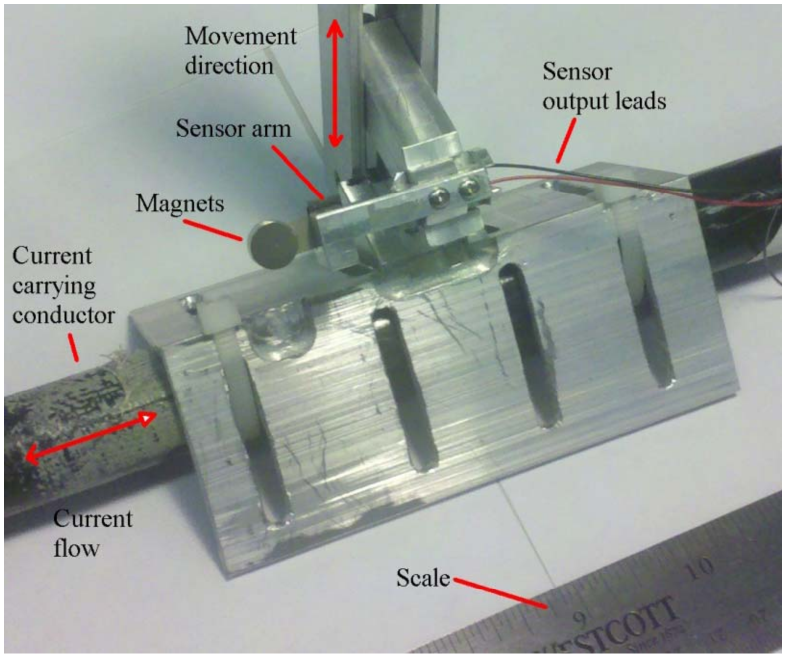


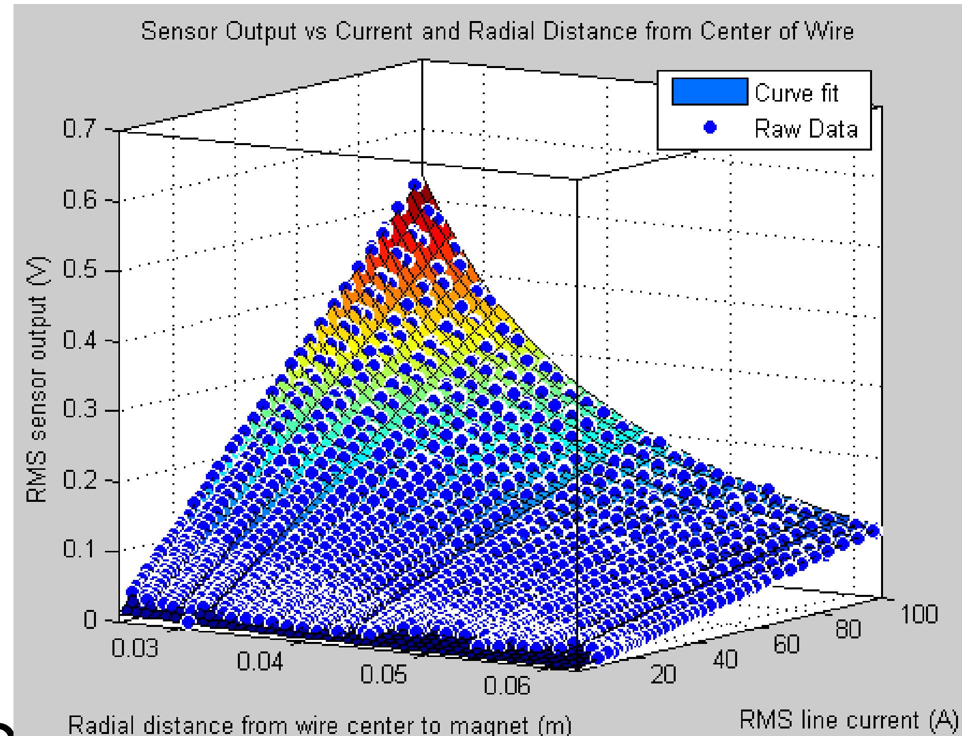




Self-calibration

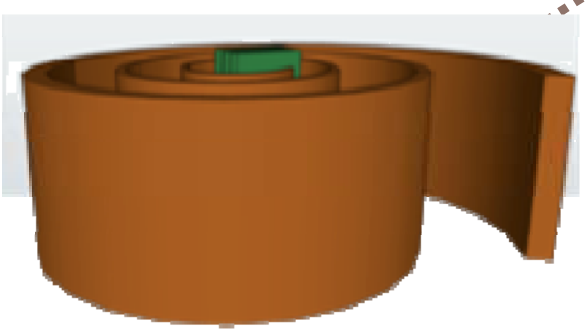




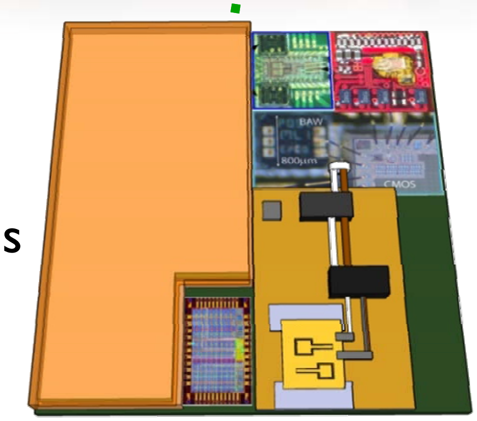


- Tests performed using meso-scale devices
- Self calibration possible using multiple devices

Multi-source Energy Harvesting



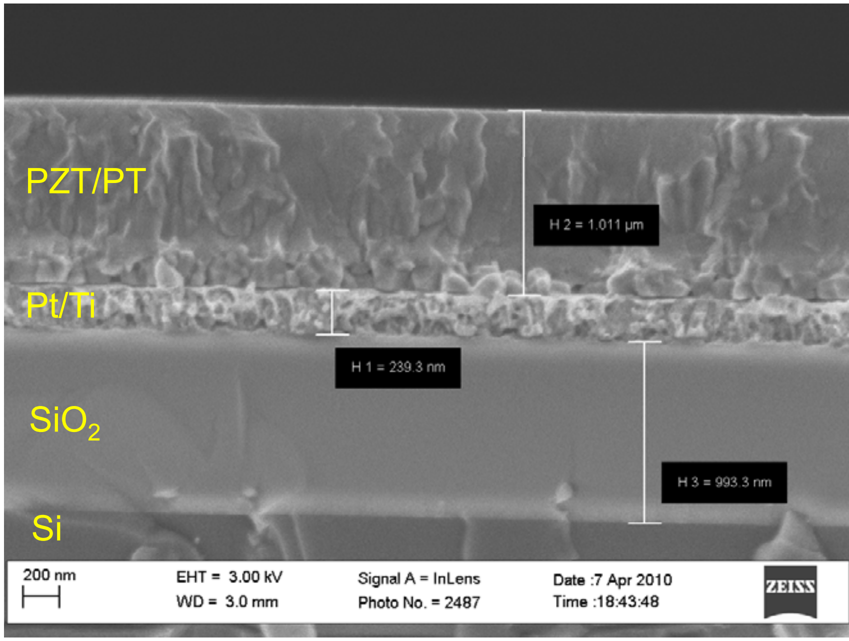
“Smart Roll”
Thermoelectric Wireless
Sensor Node



“Smart Stamp”
Piezoelectric Wireless
Sensor Node

Fabricating PZT Thin Film

Sol-Gel
Sputtering
MOCVD (Metal Organic Chemical Vapor Deposition)
PLD (Pulsed Laser Deposition)



Advantages of Sol-Gel Method

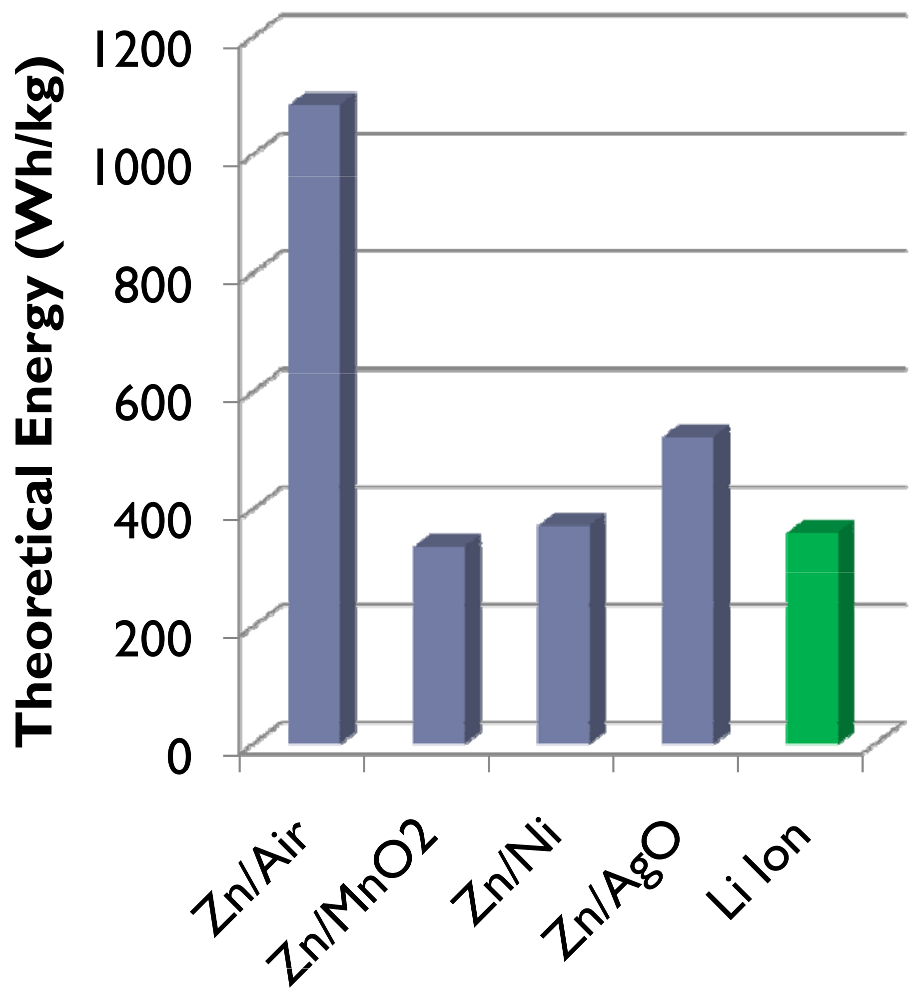
Low cost
Easy facilities
Easily control the composition
Low residual stress

Main Steps of Sol-Gel Method

Sol solution preparation: PZT(53/47)
Substrate: Pt(111)/Ti/SiO_2/Si(100)
Spin coating
Annealing

Zinc as a material for batteries

- High specific energy and volumetric energy density
- Electrochemical reversibility
- Compatibility with numerous electrolytes
- Low cost of materials
- Low manufacturing costs
- Easily recycled

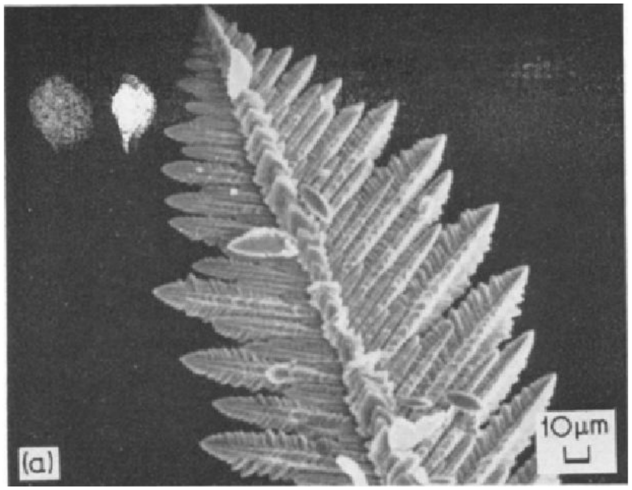


. . . the problems (aqueous electrolytes)

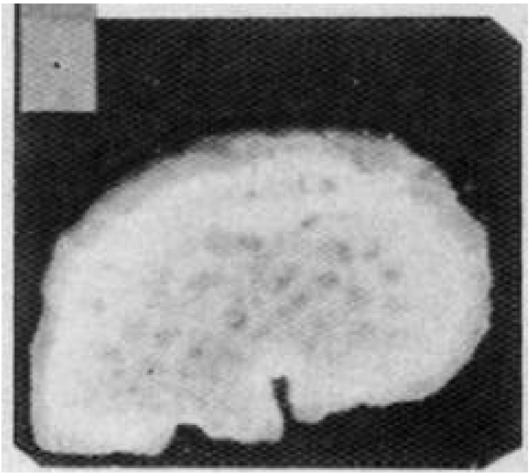
Zinc electrode is not (yet) rechargeable for over 300 cycles

(no commercial systems)

- Formation of detrimental morphologies (dendrites, filamentary growth, nodules)
- Redistribution of zinc (shape change, densification)



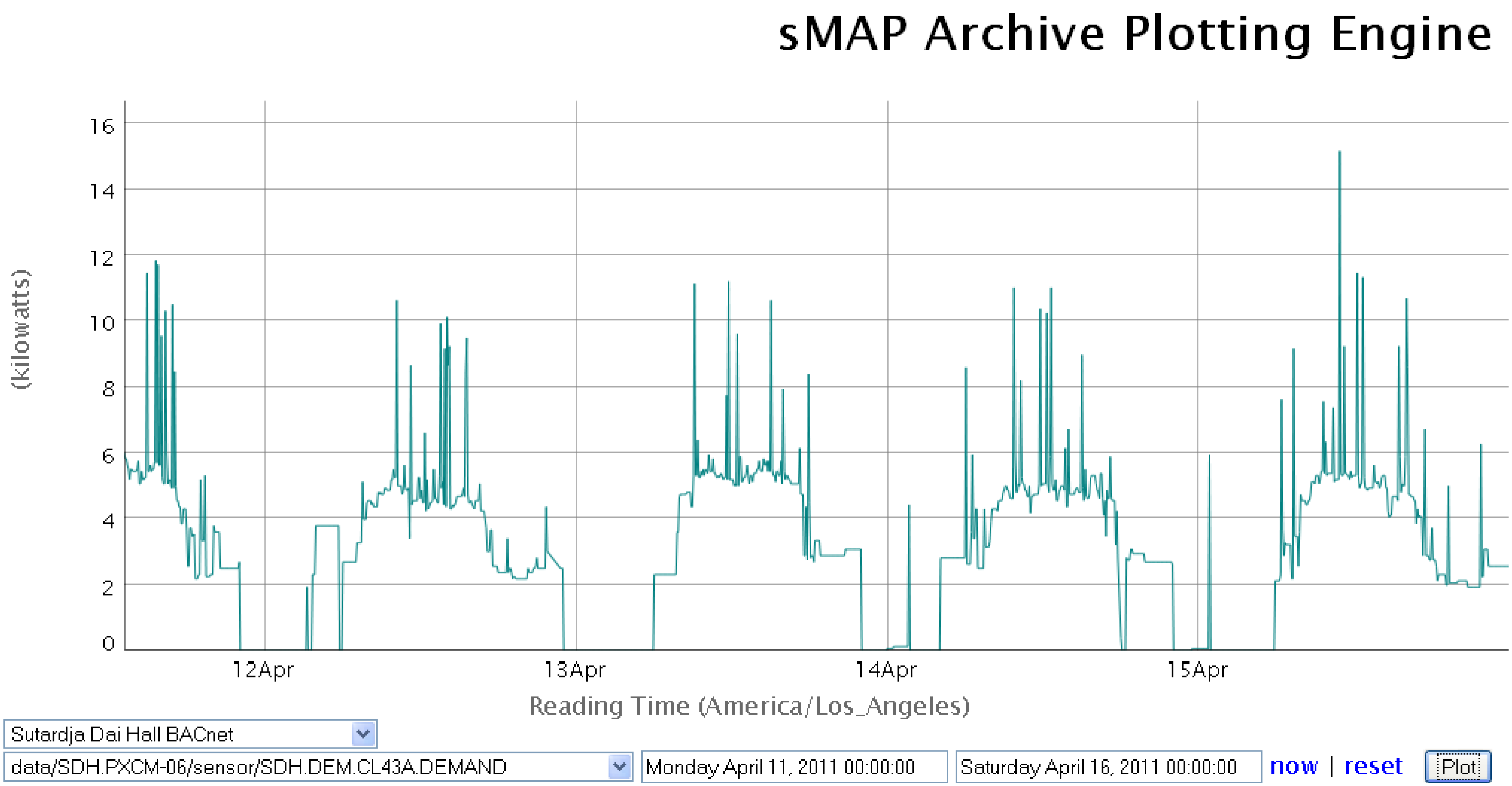
Zinc dendrite formed during deposition in alkaline solution [2]



Shape change of zinc electrode after cycling 280 times [1]

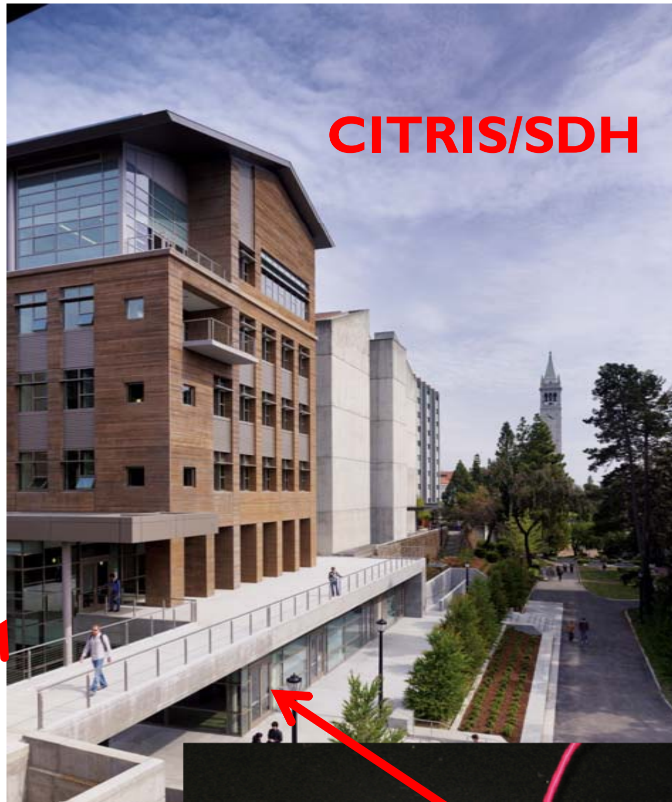
[1] McLarnon and Cairn (1991). *J. Electrochem. Soc.* **138**(2). Pages 645-54.
[2] Diggle et al. (1973). *J. Mater. Sci.* **8**. Pages 79-87.

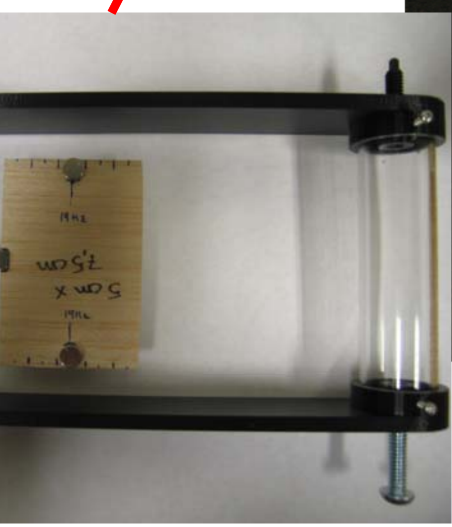
3rd Floor Lighting Data
Monday April 11th thru Friday April 15th 2011

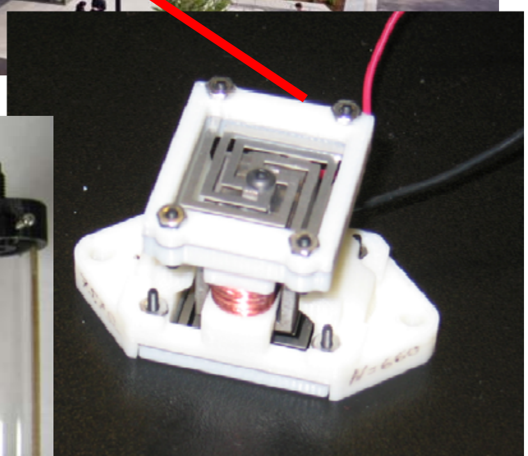


Center for Information Technology Research in the Interest of Society

Testbeds funded by PIER and now DOE

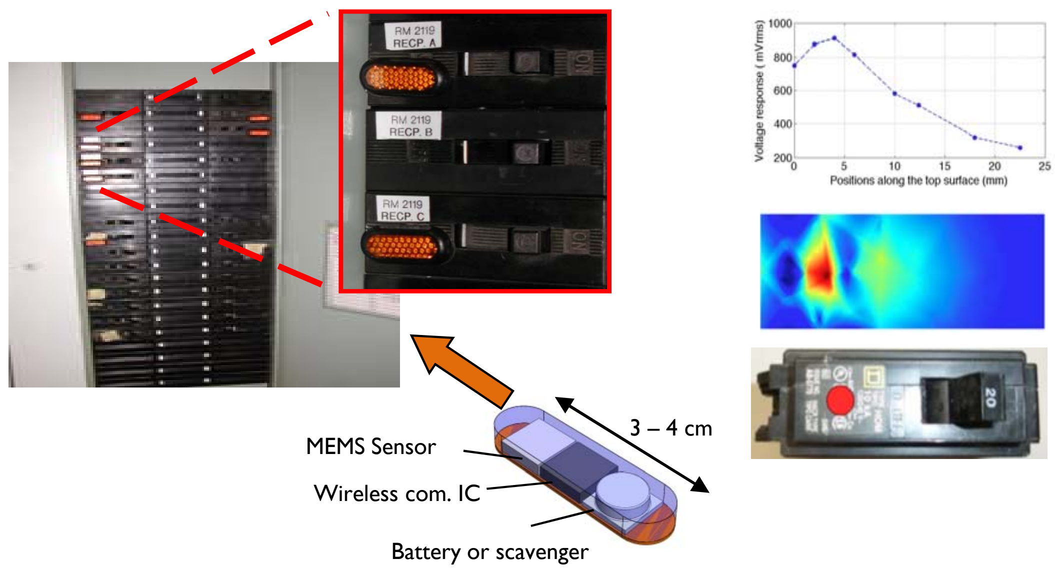






Typically 2mW

1 MW >> EECS Building--Cory Hall, built in 1953



Electric sensors couple with magnetic and electric fields due to breaker current.

Lindsay's figure one from paper

- Andrews slides

Yiping

- New – solgel – top electrode
- XRD – good crystalline structure
- D33 was 90 - 125 picometers per volt

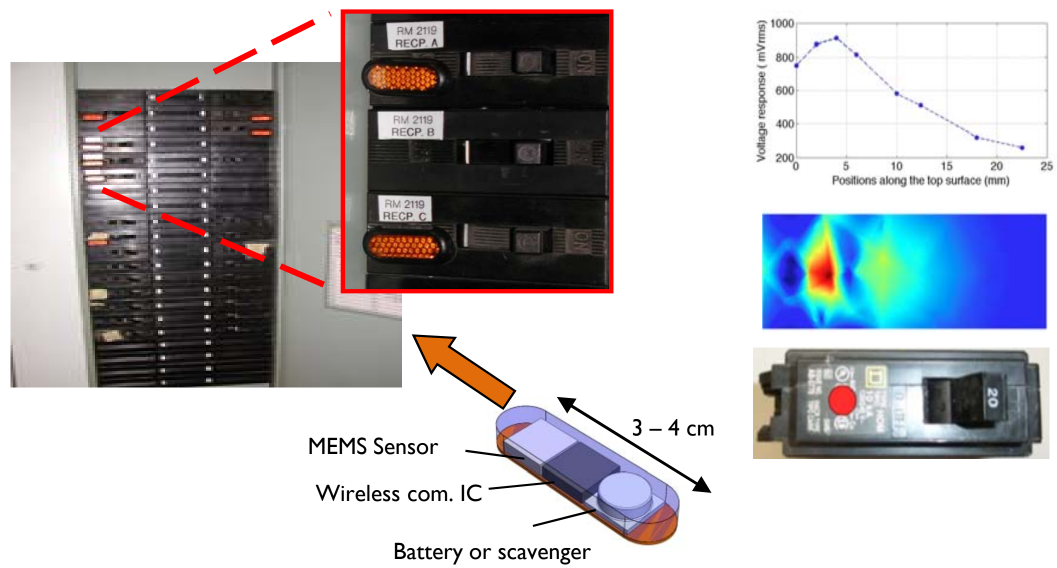
Electrical Current and Voltage sensing

- The average electric power consumption of Cory Hall is 1MW. Presently the power entering that building is metered only manually at the primary terminals of its distribution step-down transformer.

- We are designing and testing mesoscale and MEMS-based electric sensors for real-time current, voltage and power monitoring. Our sensor technology will allow us to monitor current and voltage through existing banks of standard circuit breakers.

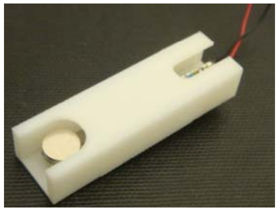
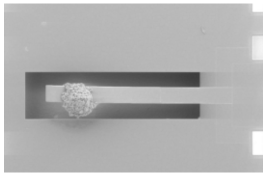
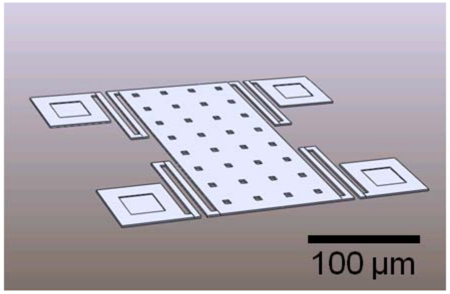
- Automated monitoring will be achieved using commercially available equipments, such as TI motes.

EECS Building--Cory Hall, built in 1953



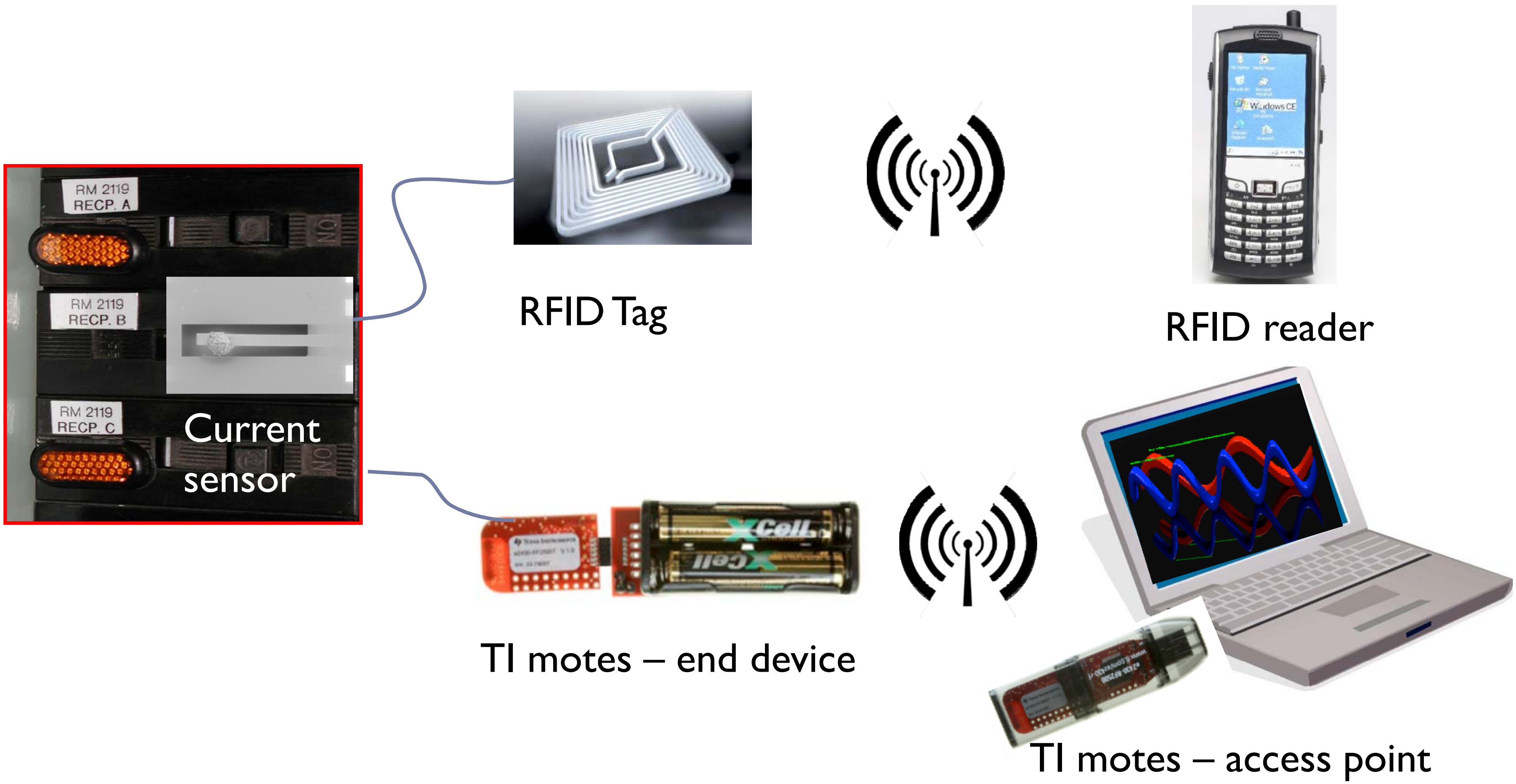
Electric sensors couple with magnetic and electric fields due to breaker current.

Sensing Technology

	Current sensor	Voltage sensor (under development)
Structure	Piezoelectric cantilever with permanent magnets mounted on its tip	A MEMS cantilever connected to a broad capacitive pickup
Physics	Permanent magnets couples with alternating magnetic field due to breaker current. The vibration of piezoelectric cantilever produces a electric signal that is proportional to the breaker current.	Micromechanical motion induced by the variation of electric field provides a measure of the electric potential.
Design & Prototype	 	

Wireless Communication

1. **RFID technologies**
2. **Texas Instruments, eZ430-RF2500 radio motes**



Future work

- Test MEMS-scale current sensors to determine sensitivity, linearity, and transient response.

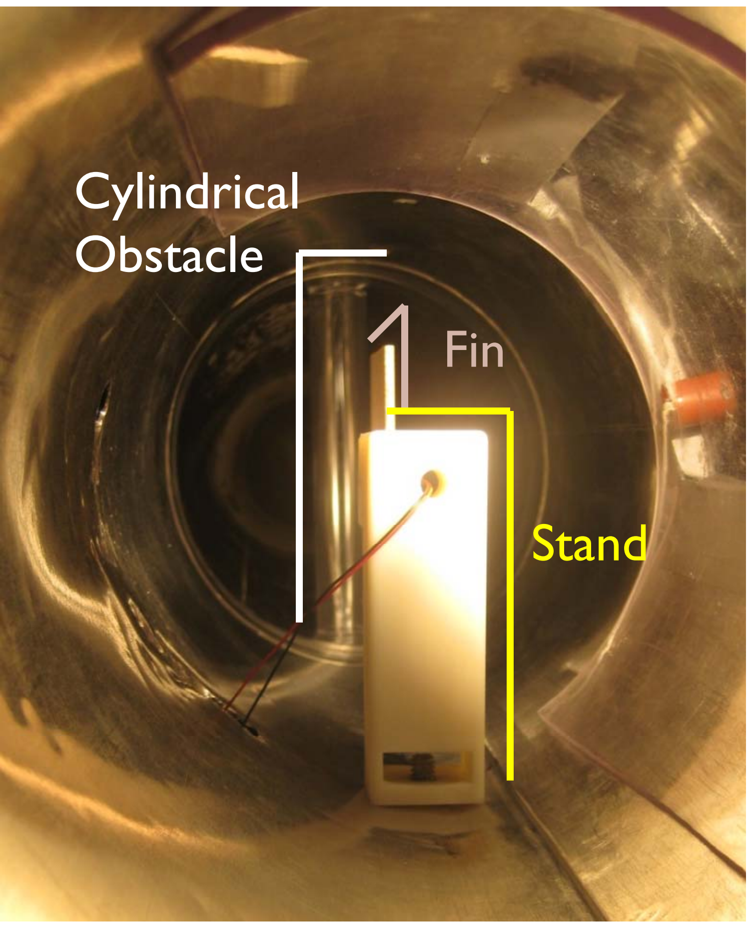
- Construct and test the sealed energy-scavenger (shown below) module to determine its suitability for powering wireless units AC magnetic and/or electric fields.

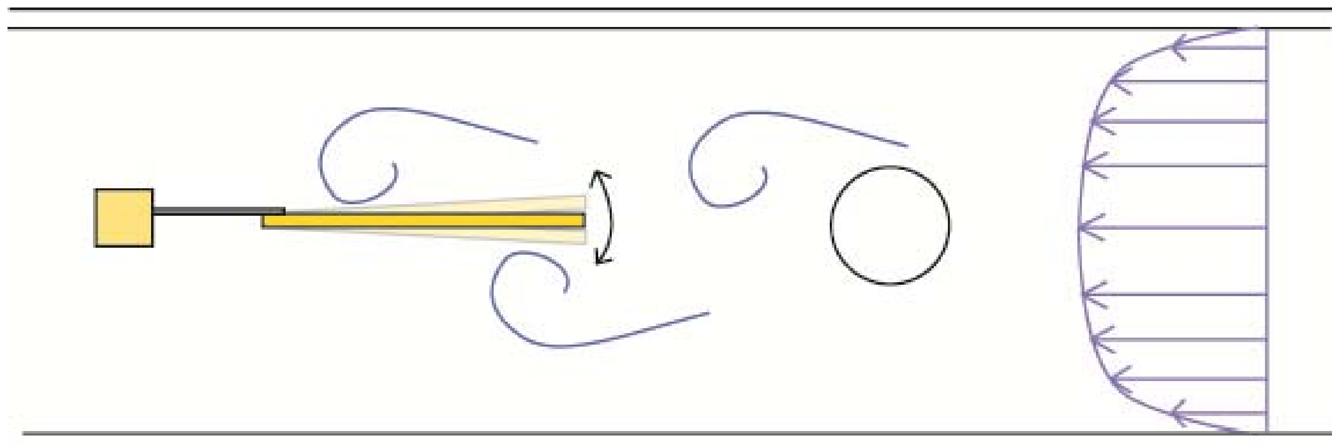
- Study sensor designs for capturing and reporting features such as power-line transients and load signatures.

- Finalize voltage sensor design.

Cylindrical Obstacle Flow Scavenger

We have had the most success with a rectangular flat plate in the wake of a cylindrical obstacle.



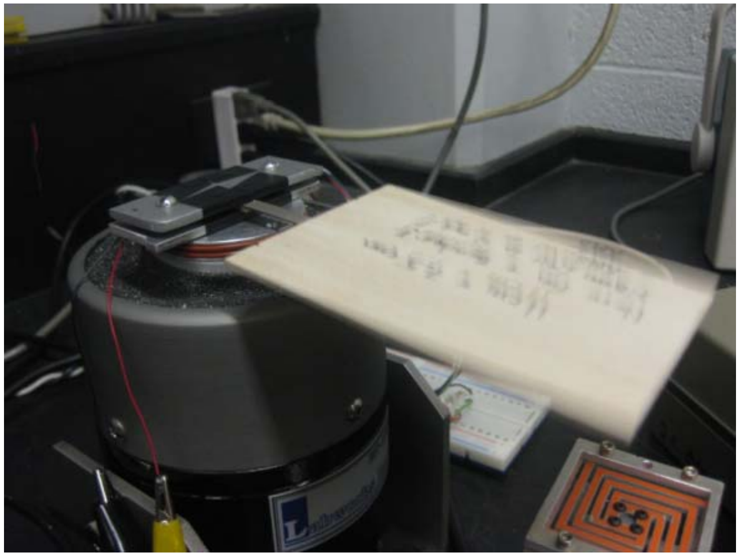


The Reynolds numbers associated with the flows in the pipe are in the turbulent range. This presents many challenges.

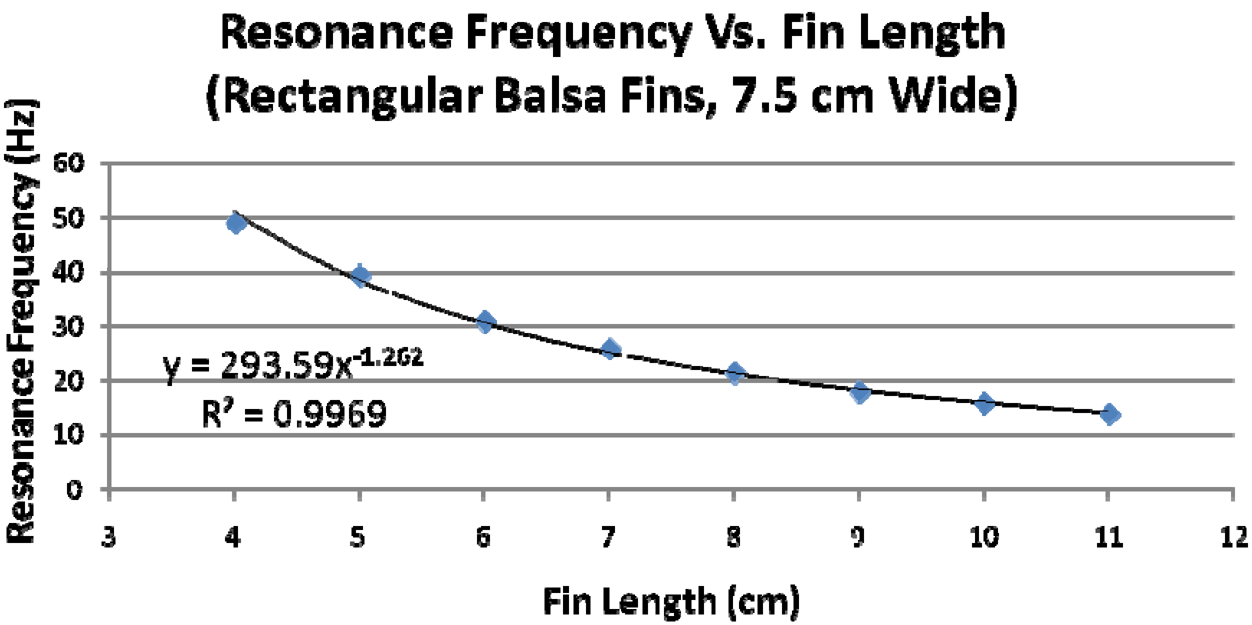
Design parameters for this setup include:
- Cylinder Diameter
- Fin material
- Fin length and width
- Separation distance between cylinder and fin

Natural Frequency of Bender & Fin

We have measured the natural frequencies of different fins using a shaker table setup. Varying the length and width of the fin gives good control over the bender's natural frequency.



Using fin materials with different densities also affects natural frequency. Balsa wood is the best material for our needs that we have tested so far.



Vortex Shedding Frequency

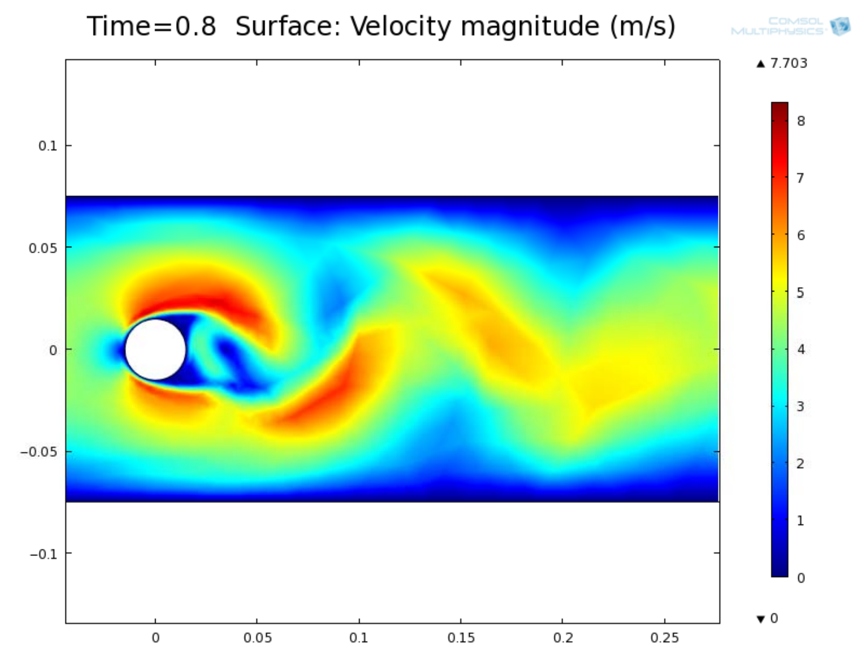
Certain obstructions in flows, such as cylinders, have periodic vortex shedding.

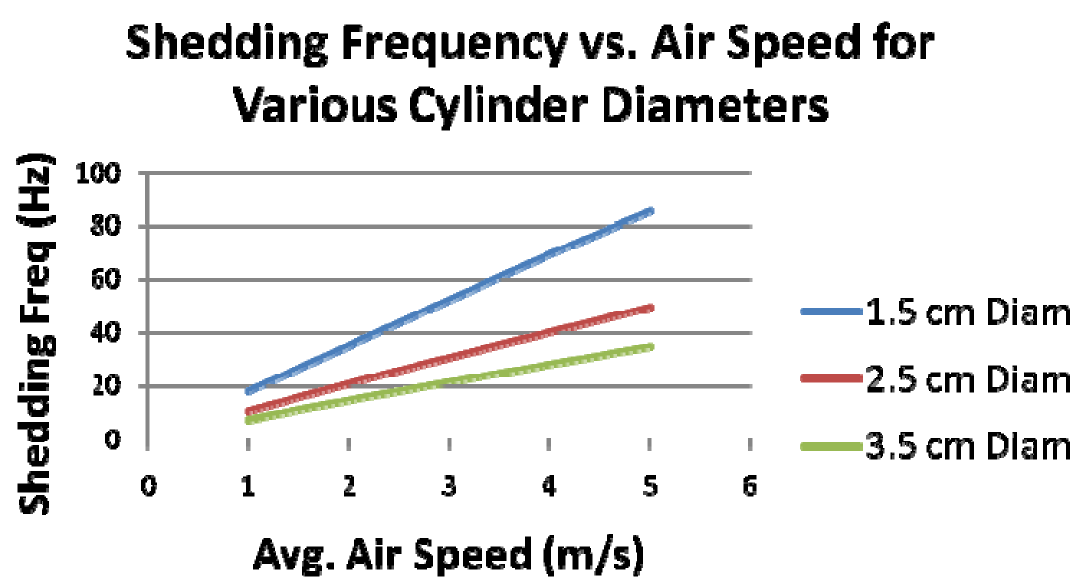
We have used COMSOL as well as Strouhal number relationships from the literature to model the shedding frequency from the cylinder.

$$f = \frac{St * v}{D}$$

$$St = St^* + \frac{m}{\sqrt{Re}}$$

For Re > 5000,
St* = 0.1776
m = 2.2023



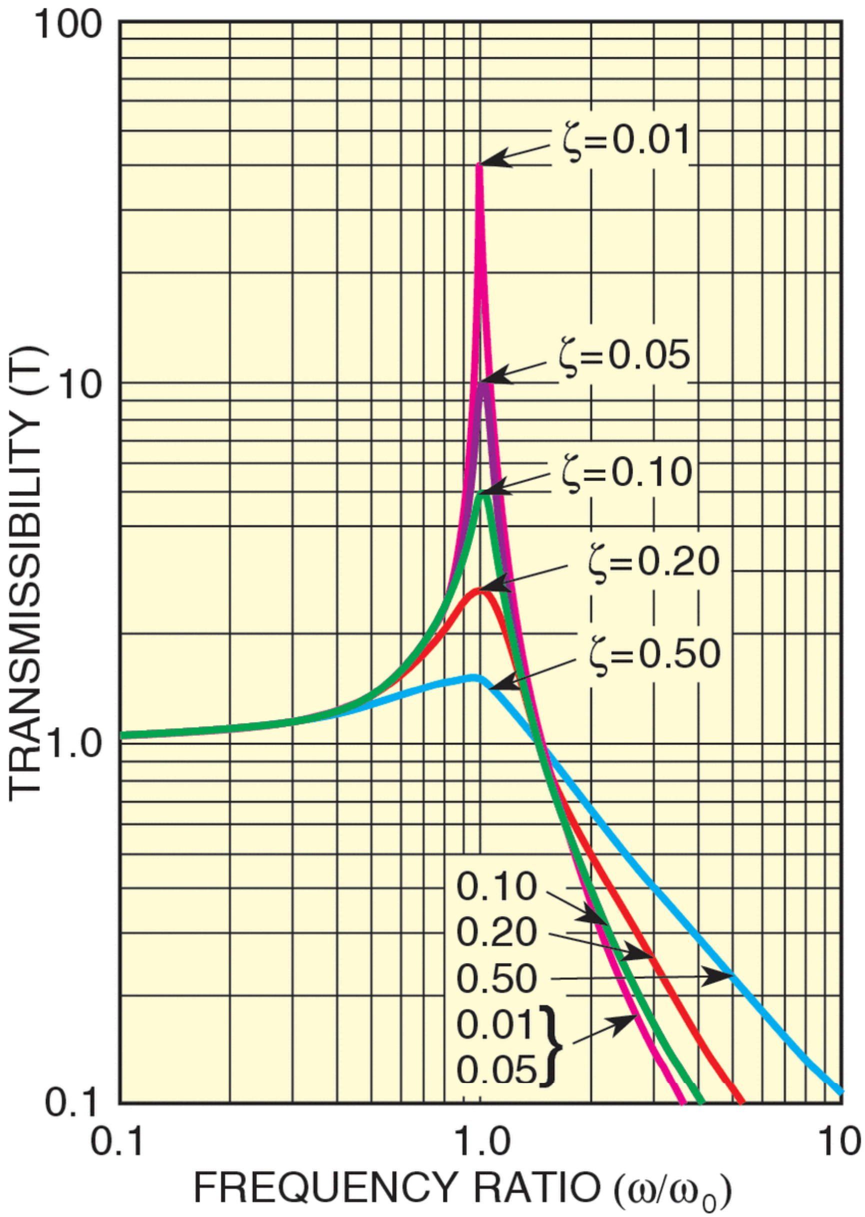


Damped Oscillator Response

The bender and fin can be modeled as a damped oscillator. Because of the way damped oscillators respond to periodic inputs, matching frequencies is essential for high performance.

The relationship between input force and power out (transmissibility) is based on the ratio of input frequency to resonance frequency. This is calculated through the equation below and shown in the figure to the right for various damping coefficients.

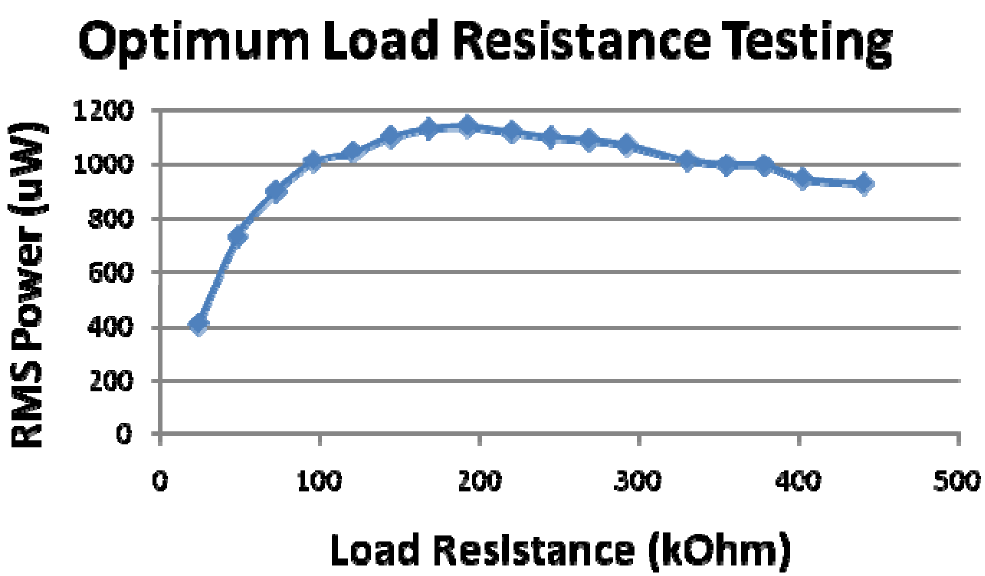
$$T = \frac{|x|}{|u|} = \sqrt{\frac{1 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2}{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2}}$$

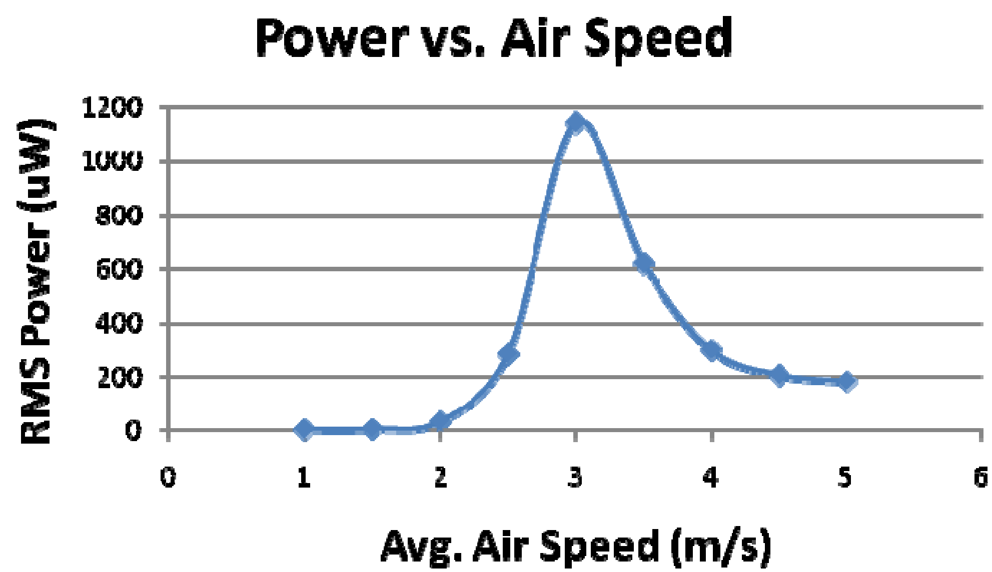


Performance

Successful trials have shown power outputs of 1 mW and higher for certain configurations.

For results shown:
Fin dimensions: 7.5 cm wide x 7 cm long
Cylinder Diameter: 2.5 cm
Optimum Load Resistance: 194 kOhm



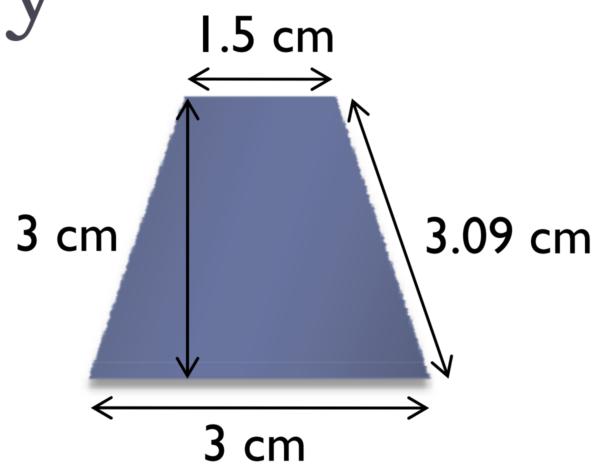


Flow Speed	1m/s	1.5 m/s	2 m/s	2.5 m/s	3 m/s	3.5 m/s	4 m/s	4.5 m/s	5 m/s
RMS Power	2 uW	4 uW	31 uW	282 uW	1140 uW	619 uW	298 uW	205 uW	181 uW

Piezoelectric Bender Geometry

Motivation for Trapezoid

- Triangles are the most optimal at uniformly distributing stress, but difficult to build and implement.
- Using Finite Element Analysis (FEA) methods, a trapezoid geometry was designed to concentrate stress at the base of piezoelectric harvester.



Choosing an Operating Frequency

Design Parameters

- a, Input acceleration
- f_{op}, Desired operating frequency
- M, Added end mass

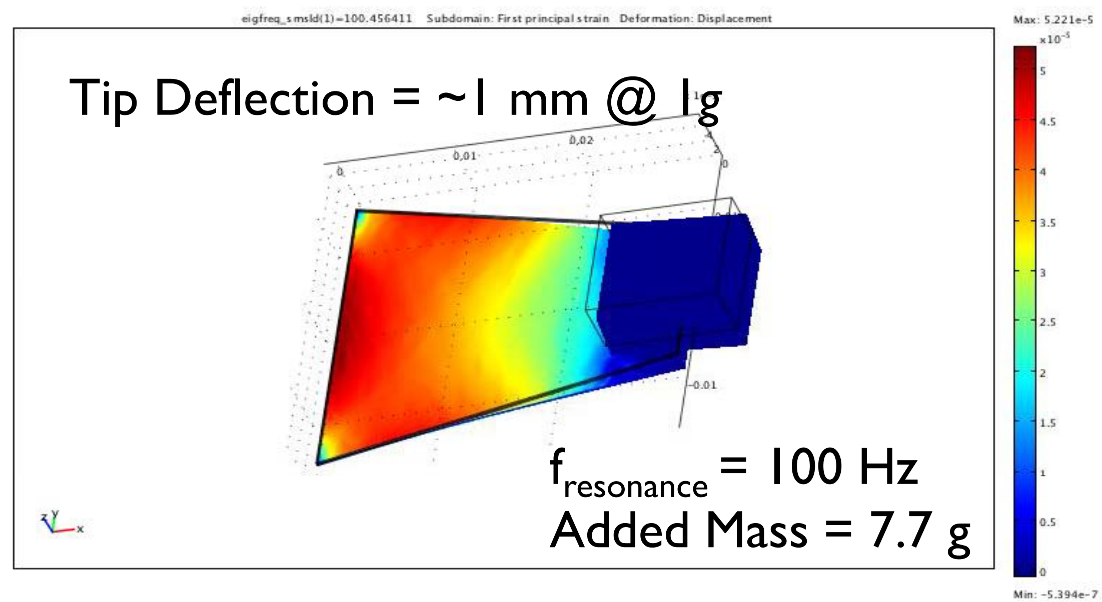
For maximum power output:

$f_{op} = f_{resonance}$ ➔ $f_{resonance} = (k/m)^{1/2}$

Tune bender's resonant frequency by adding mass at the tip of trapezoid.

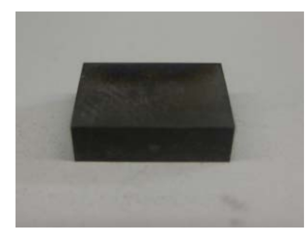
For f_{op} = 100 Hz use M = 7.7 g

For f_{op} = 120 Hz use M = 4.9 g

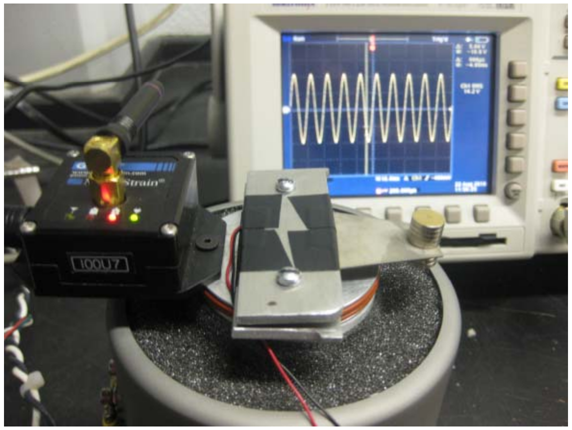


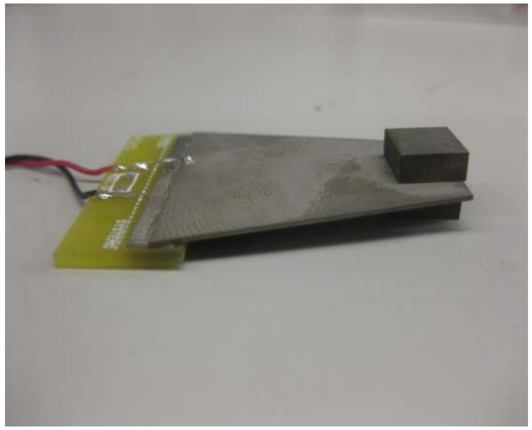
End mass realized as a block of Tungsten glued to bender tip.

$\rho_{tungsten}$ = 19.3 g/cc



Power Performance





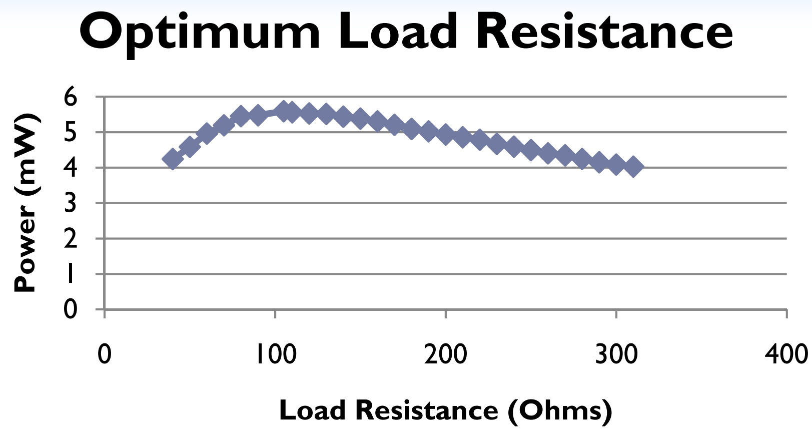
Device performance is tested on a shaker table equipped with an accelerometer to produce the following plots.

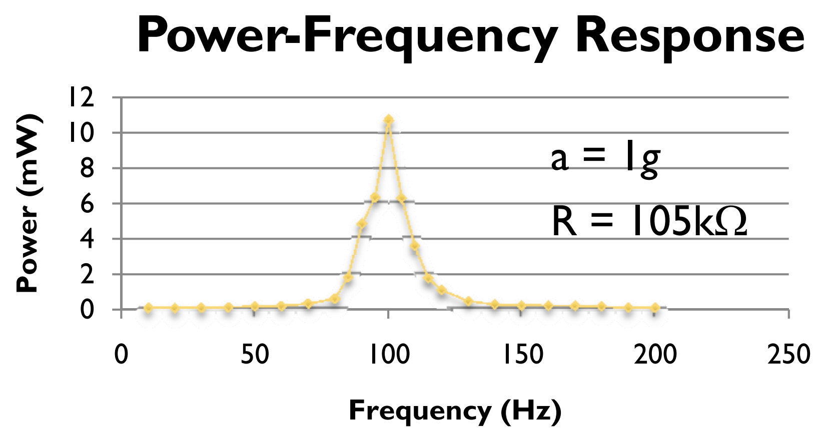
The optimum load resistance was found to be:
$R_{optimum}$ = 105kΩ

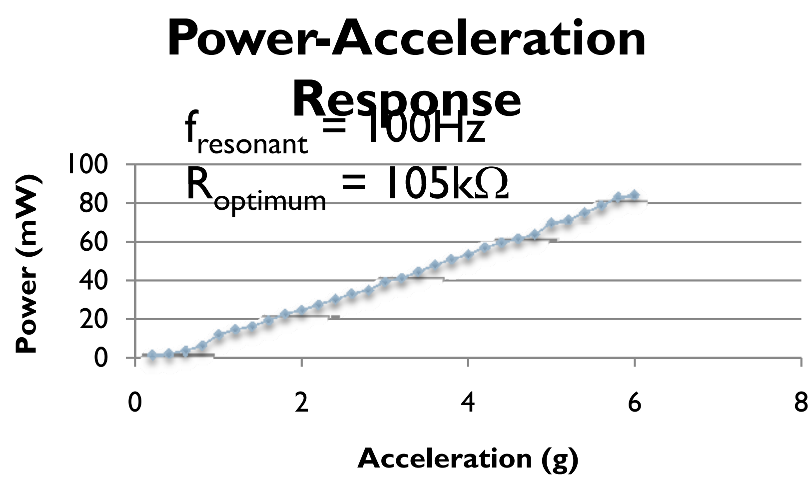
Given a sinusoidal input and constant acceleration the following power out for the desired operating conditions are:

For a = 0.05g P = 28μW

For a = 1g P = 10.4mW



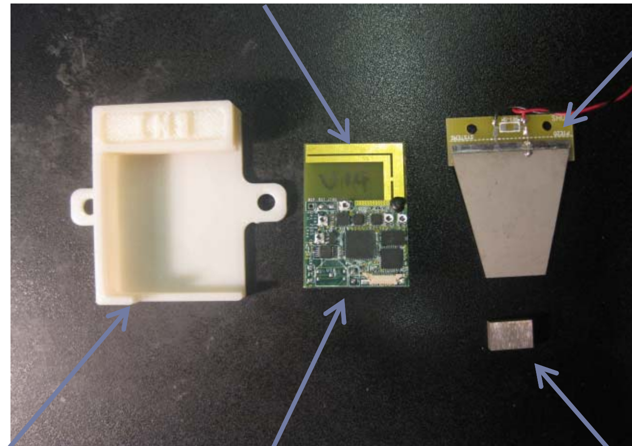


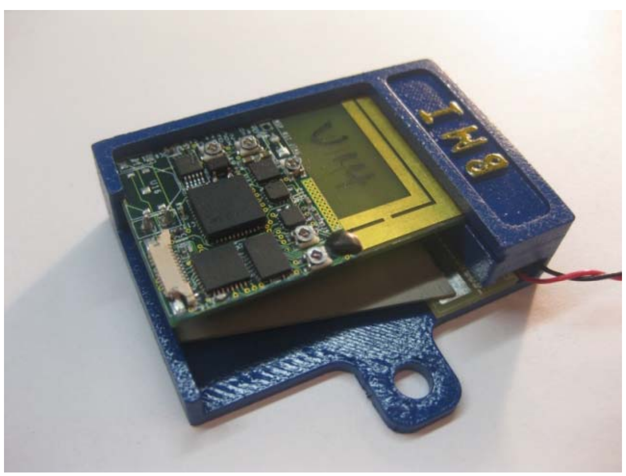


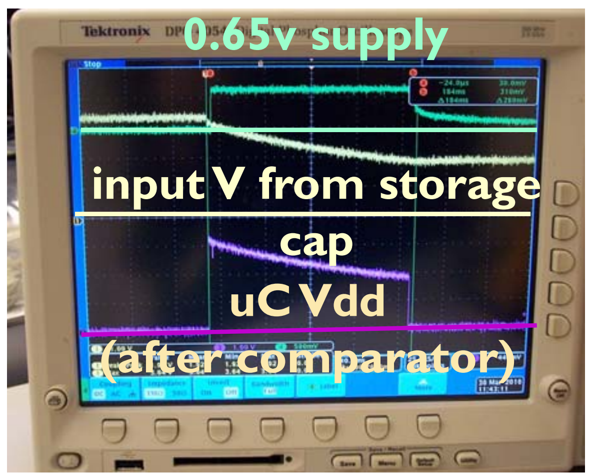
Device Integration

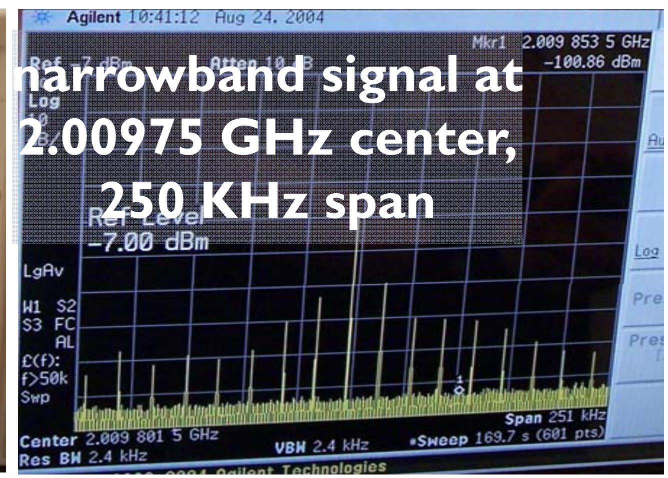
Demo: Powering a radio and accelerometer

Device screwed down to a shaker table with 1g sinusoidal excitation, the vibration scavenger powers a circuit board which samples data from an onboard accelerometer and wirelessly transmits a packet of sensor data.





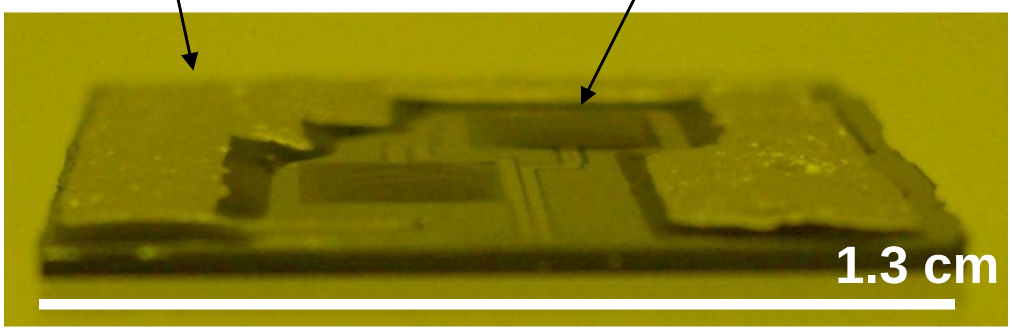


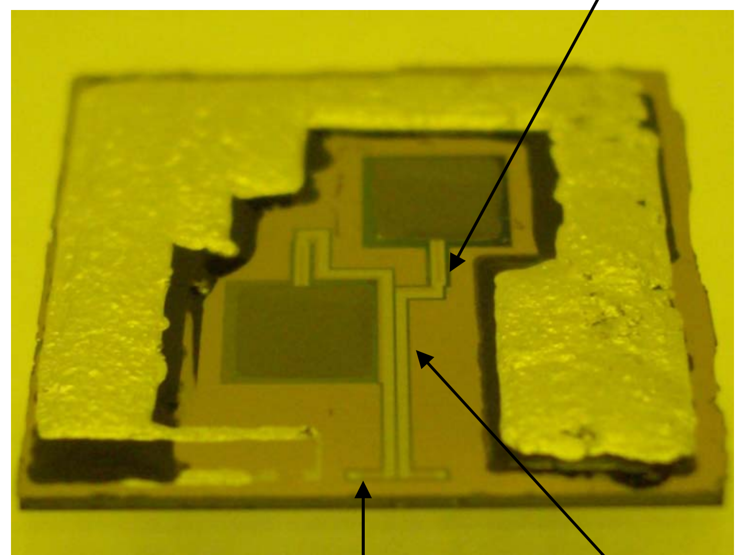


Given a 10 second charge time and two packets per Tx event, duty cycle ("on" time / "off" time) is about 0.2%

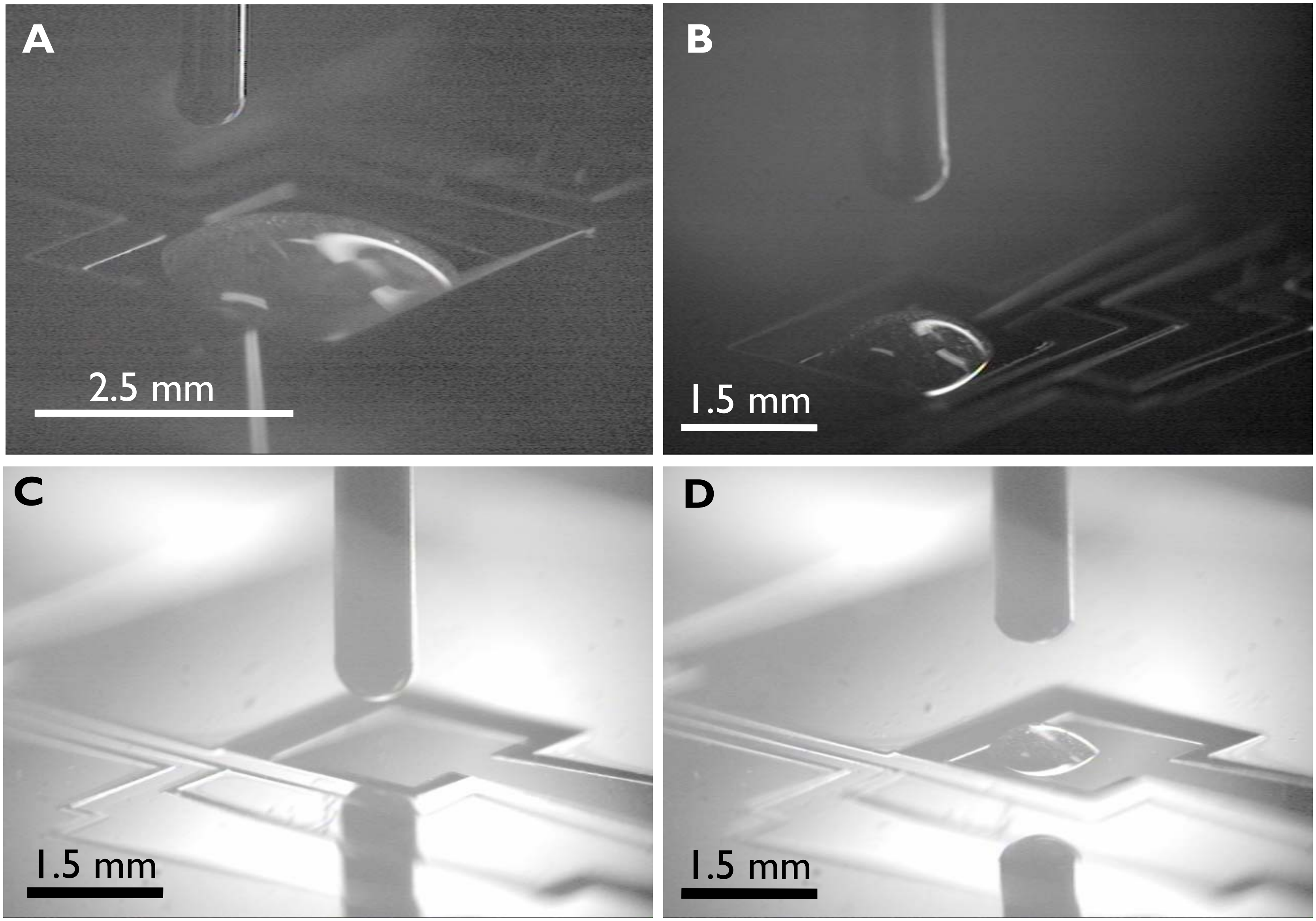
Here is the chip with printed storage:

This is the first phase of work to integrate energy harvester with energy storage





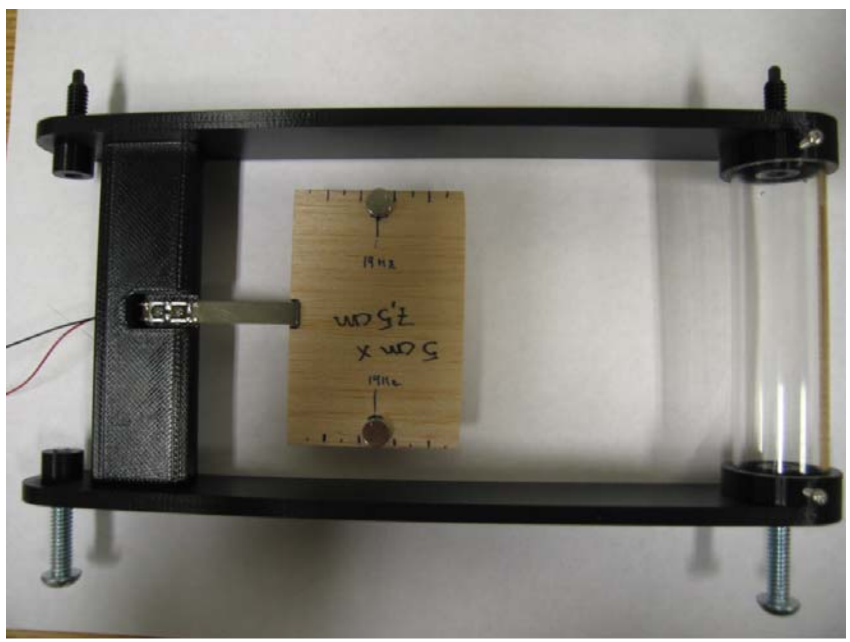
Alic and Lindsay successfully printed mass on 6 released beams in order to modify the resonance frequency. There were no "casualties".



- Advantages with printing
  - Fast
  - Easily scalable
  - Done after completion of all microfabrication steps including release
  - Done in ambient conditions
  - Non-destructive
- Future possibilities
  - Print the capacitor and battery as the mass of the beam
  - Improve power density by using printed mass to utilize 3D space instead of needing to expand in the area of the Si wafer

New Mount Design

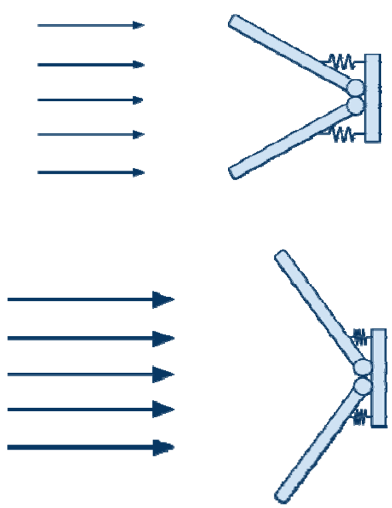
- Spring plungers allow use in various duct geometries without compromising stability
- New mount showed as much as 40% increased power output compared to old mounts

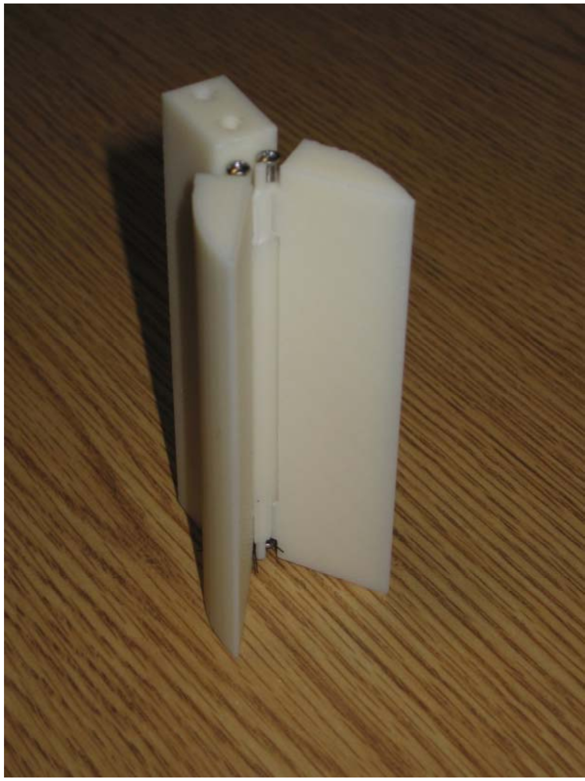


Future Work: Self-Tuning Obstacle

- Current design relies on resonance that only occurs in a small range of air speeds
- A self-tuning obstacle could achieve resonance at all wind speeds

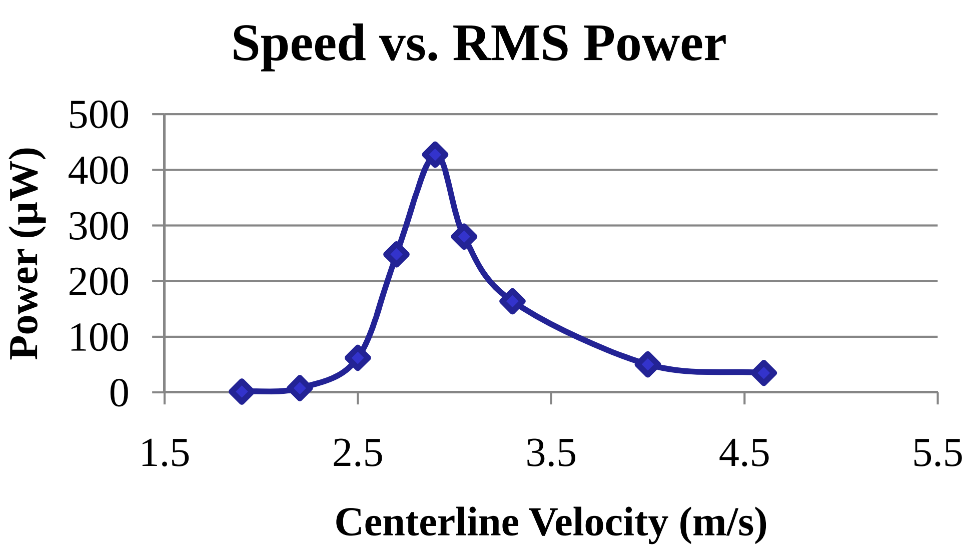
$$f = \frac{St * v}{D}$$





Future Work: Self-Tuning Obstacle

Power vs. air speed for a given configuration:



Power vs. air speed with all points taken at resonance: