Ultra-High Power Density Piezoelectric Energy Harvesters

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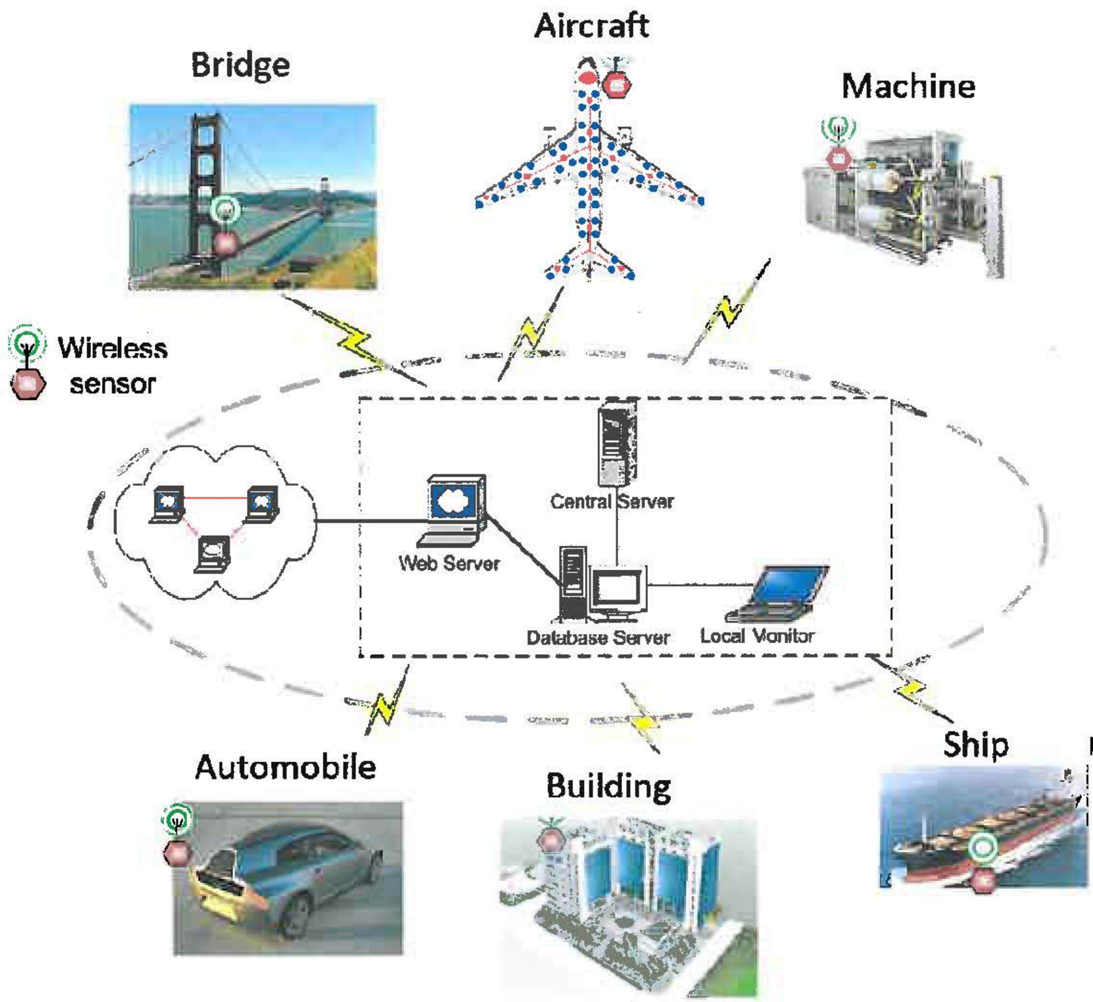
Outline

- Introduction: Background and motivation
- Methodologies for harvesting more electrical energy
  - Enhanced mechanical energy capture
  - Increased mechanical to electrical energy conversion efficiency
  - Increased energy storage efficiency
- Experimental results and validation
- Low cost piezoelectric harvester
- Conclusions

Piezoelectric Energy Harvesting Applications

Structural health monitoring



Power for portable devices

A soldier with
portable electronics

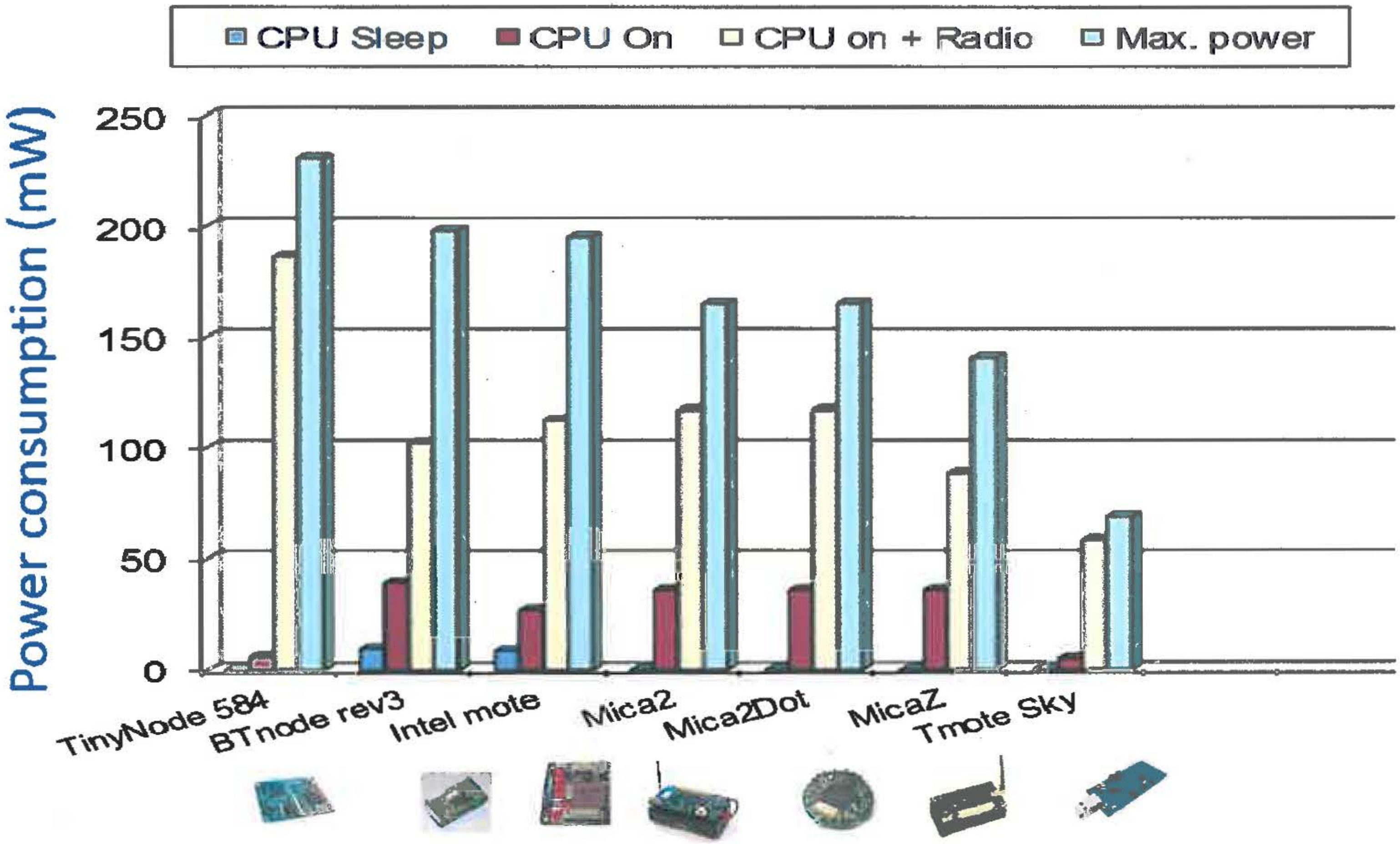
Smartphone

Vibration Sources

Vibration source	Acceleration		Frequency $_{peak}$ (Hz)
	(m/s^2)	G (9.8 m/s^2)	
Car engine compartment	12	1.22	200
Base of 3-axis machine tool	10	1.0	70
Blender casing	6.4	0.65	121
Clothes dryer	3.5	0.36	121
Person tapping their heel	3	0.31	1
Car instrument panel	3	0.31	13
Door frame just after door closes	3	0.31	125
Small microwave oven	2.5	0.26	121
HVAC vents in office building	0.2 - 1.5	0.02 - 0.15	60
Windows next to a busy road	0.7	0.07	100
CD on notebook computer	0.6	0.06	75
Second story floor of busy office	0.2	0.02	100
Railway	1.078 - 1.568	0.11 - 0.16	12 - 16
Truck	1.96 - 3.43	0.2 - 0.35	8 - 15
Ship	0.98 - 2.45	0.1 - 0.25	12 - 13

Smart. Mater. Struct. 17 (2008) 043001; MRS Bulletin 37 (2012) 1039.

Power Consumption of Wireless Sensors

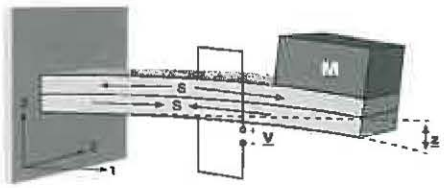


➤ Wireless sensors need power sources on the order of 100 mW

http://www.btnode.ethz.ch/Projects/SensorNetworkMuseum

State-of-the-Art
Piezoelectric Energy Harvesters

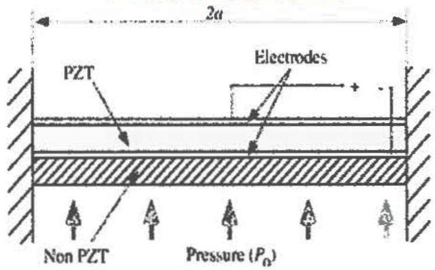
Cantilever Beam-based Harvesters



S. Roundy and P. K. Wright, Smart Mater. Struct. 13(5), 1131–1142, 2004

- 0.2μW ~4 mW
- Resonance mode operation
- >1000 papers

Edge Clamped Circular Diaphragm Harvesters

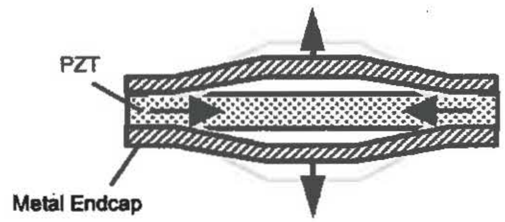


Kim, S., W. W. Clark and Q.-M. Wang, Journal of Intelligent Material Systems and Structures, Vol. 16: 847-854, 2005

- 1~20 mW
- High resonance frequency > 1000 Hz
- Suitable for acoustic pressure

Flextensional Harvesters

- Cymbal



Kim, H.-W., A. Batra, S. Priya, K. Uchino, D. Markley, R. E. Newnham, and H. F. Hofmann, 2004, JJAP Vol. 43, No. 9A, pp. 6178–6183

- 52 mW of electrical power to a 400 kΩ matched resistive load under 70 N_{rms} force at 100 Hz
- Energy conversion efficiency: 7.8%

Multilayer stack

Sosnicki, O., N. Lhermet, F. Claeyssen, ACTUATOR 2006, 14 – 16 June 2006, Bremen, Germany

- 50 mW electrical power at the resonance frequency of 110 Hz with 0.85g acceleration

Multidisciplinary Challenge

Vibration source	Piezoelectric element	Energy storage
coupling to active element	energy conversion efficiency and its measurement	charge transport and delivery to load
Mechanical Engineering	Materials Science	Electrical Engineering

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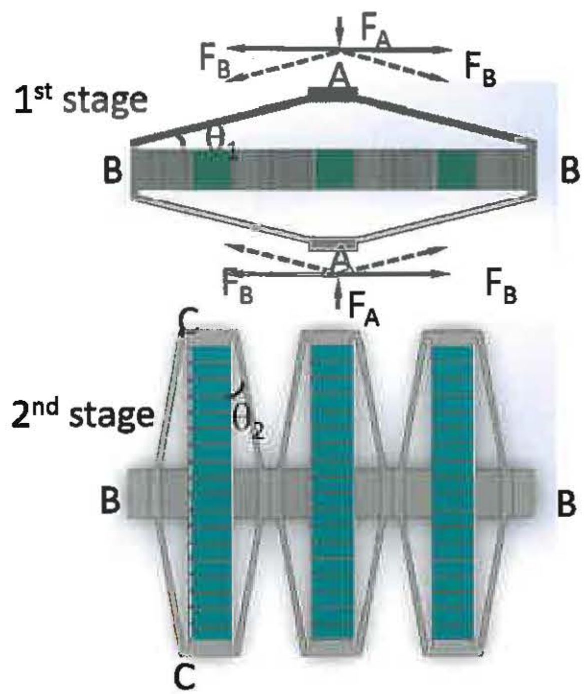
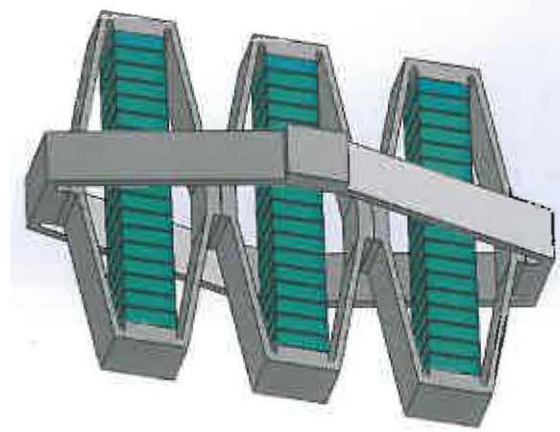
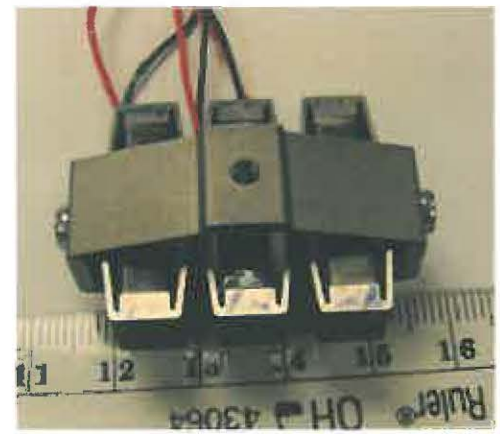
Approach I: Capture More Mechanical Energy

Two-stage Force Amplification Piezoelectric Energy Harvester (TS-FAPEH)







$$F_{CC} = \cot(\theta_1)\cot(\theta_2)F_{AA}$$

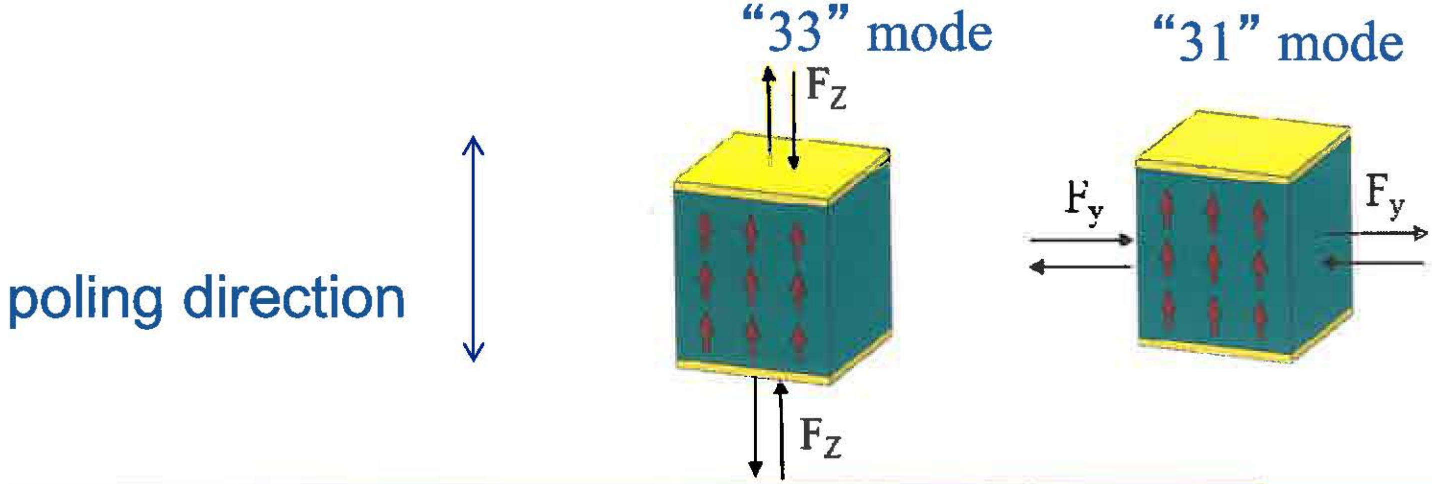
$$E \propto F_{CC}^2$$

If $\theta_1 = \theta_2 = 11°$, then **625 times** more mechanical energy can be captured/transferred into each piezoelectric element

Tian-Bing Xu, Emilie J. Siochi, Lei Zuo, Xiaoning Jiang, and Jin Ho Kang, "Multistage Force Amplification of Piezoelectric Stacks" U.S. Patent 9,048,759 B2, June 2015.

Approach II: Increase Energy Conversion Efficiency

Piezoelectric Material Selection and Mode



Property	High K HK1-HD	Type II 200-HD	Type III 300-HD	SC-PMN-32% PT*
"31" energy conversion efficiency (k^2_{31})	0.15	0.14	0.11	0.26
"33" energy conversion efficiency (k^2_{33})	0.55	0.53	0.46	0.83

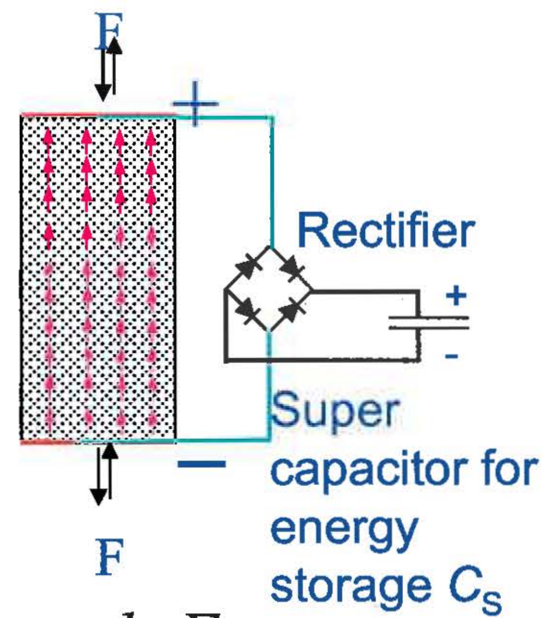
$$k_{33}^2 \approx (3-5)\,k_{31}^2$$

SC-PMN-32% PT = Single crystals of lead magnesium niobate-lead titanate

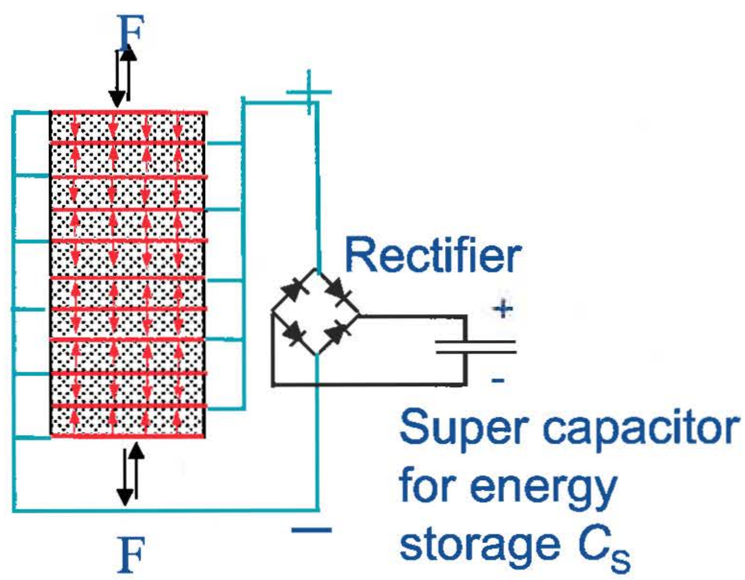
*TRS: http://www.trstechnologies.com

Approach III: Increase Energy Storage Efficiency

Optimization of Multilayer Stacks



$$q = d_{33}F$$



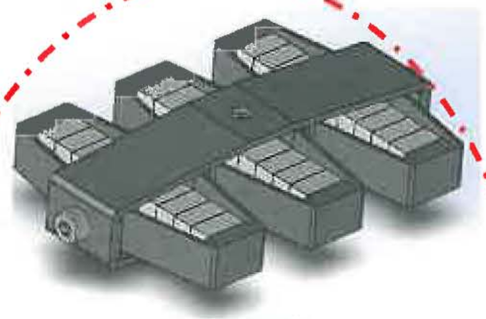
$$q = nd_{33}F$$

- Optimize number of layers, *n*, for charge generation and collection
- Stored energy $$\Delta E = \frac{2Q_0\Delta Q + (\Delta Q)^2}{2C_S} = \frac{(\Delta Q)^2}{2C_S} (if \quad Q_0 = 0)$$

where → Q_0 initial electric charge in the super-capacitor

Multidisciplinary Integration and Design Optimization

Design



Fabrication

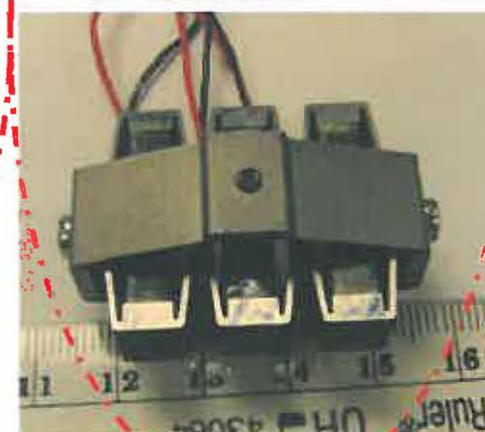
Parameters of PMN-PT Single Crystal Multilayer Stack

62 piezoelectric layers

22 mm x 5 mm x 5 mm

4.5 gram

Integration



- Frame geometry and parameters design is critical

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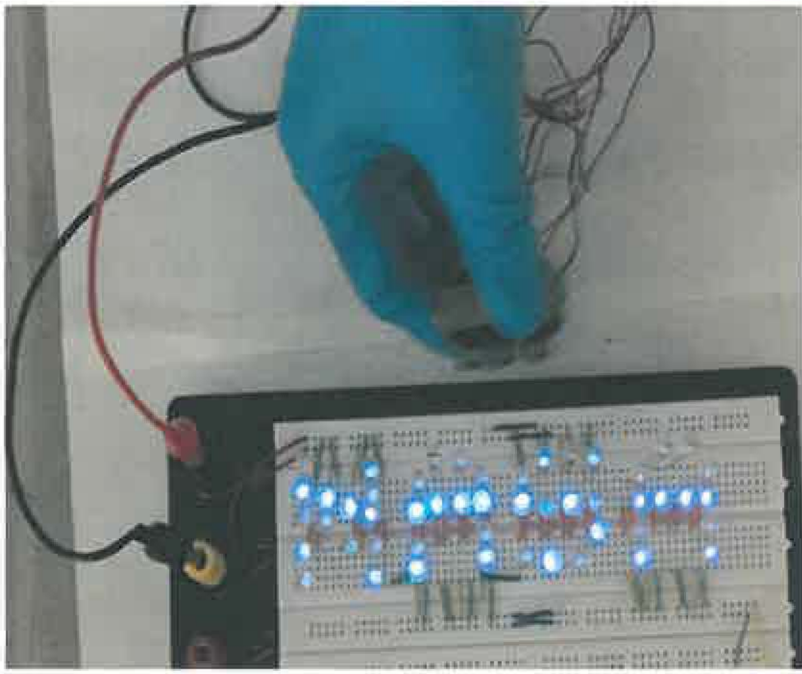
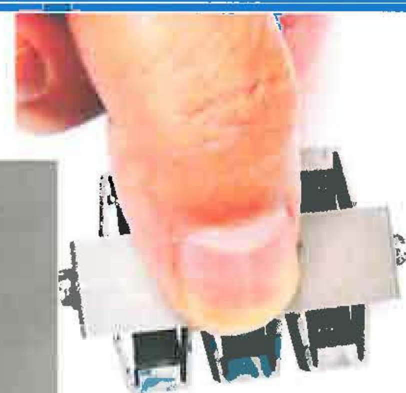
Harvesting Electrical Power

Directly Power 50 LEDs

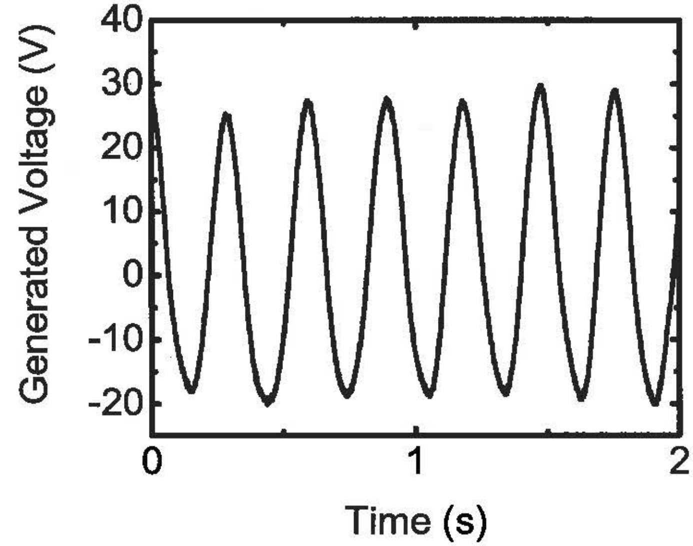




34 gram

Generated Open Circuit Voltage

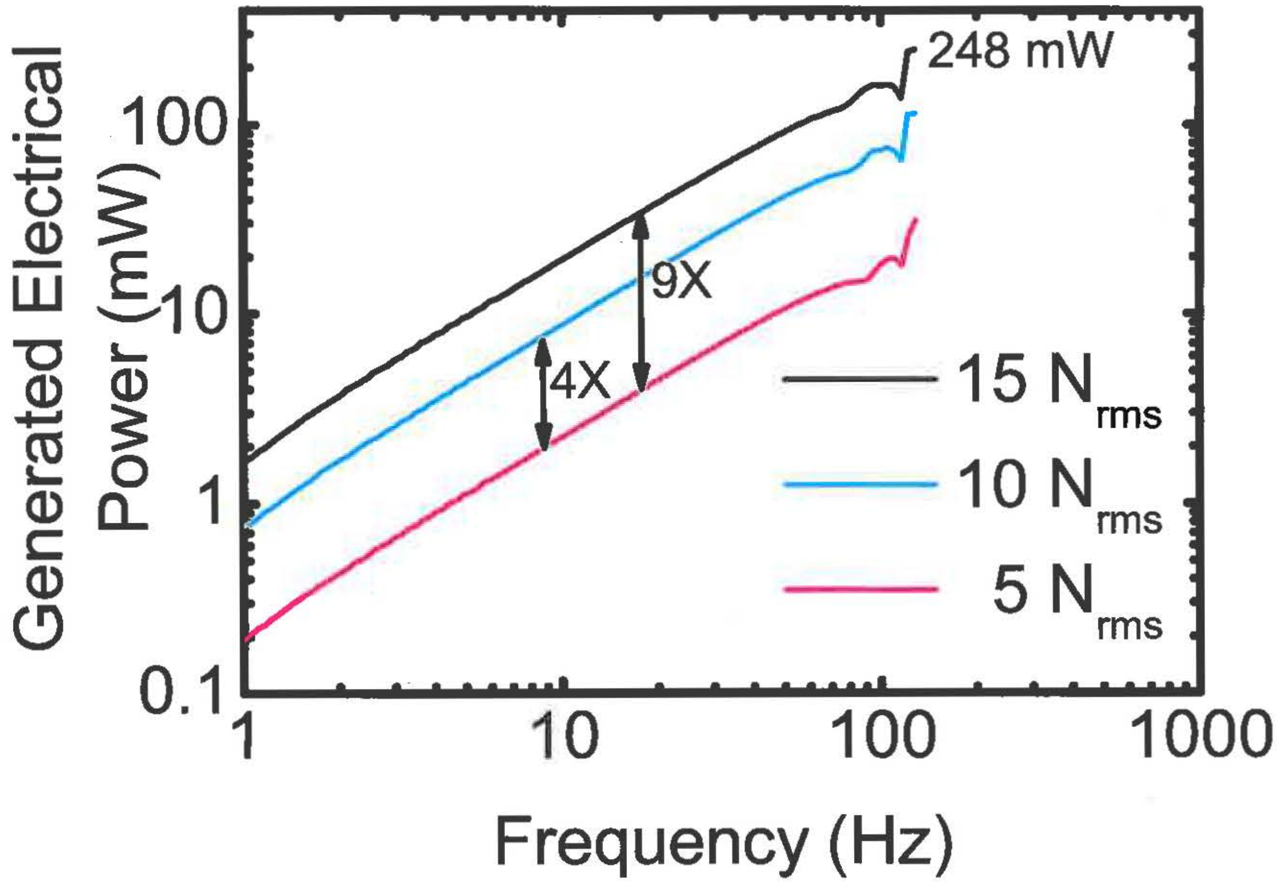
V = 18.5 V_{rms}, f = 3.25 Hz, Power = 6.0 mW



- Two finger compression can directly power 50 LEDs.

Off-resonance Mode Operation

34 gram TS-FAPEH

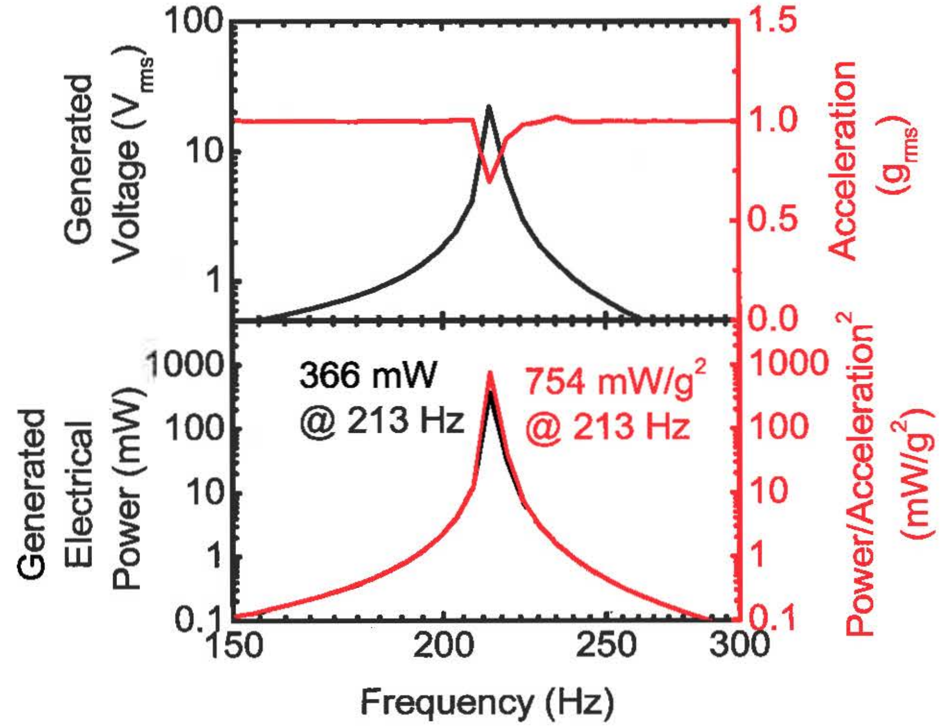


- The generated electrical power is proportional to
  - frequency
  - the square of the applied force.

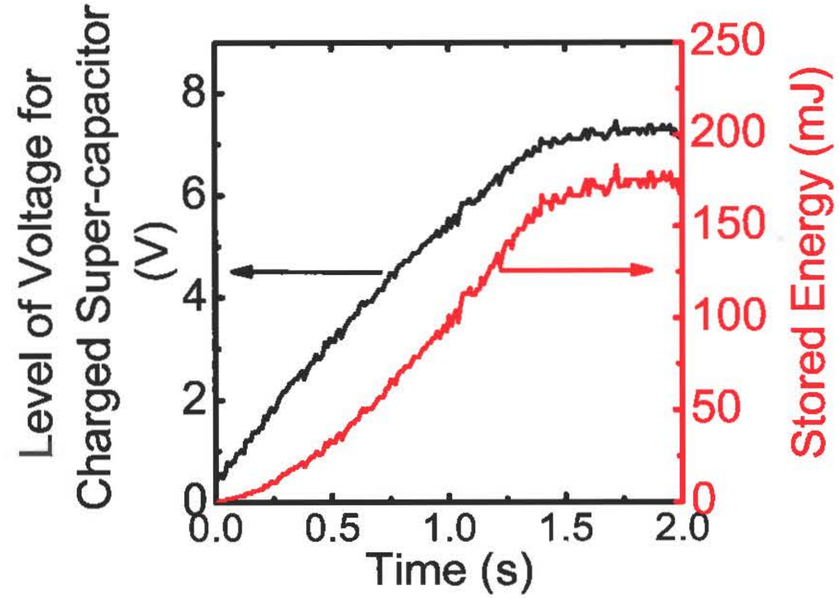
Resonance Mode Operation Without Proof Mass

34 gram TS-FAPEH

Frequency spectra



Charging a 6,600 µF Super-capacitor at 213 Hz with 1 g acceleration



- It only took 1.4 seconds to charge a 6,600 µF super-capacitor from 0 to 6.8 V (full) for 1 g_{rms} acceleration

Comparison With the State-of-the-Art Piezoelectric Energy Harvesters

Off-resonance mode operation

Harvesters	Weight (gram)	Applied force		Generated electrical power (mW)	power density normalized by weight, force², and frequency {μW/[kg.$(N_{rms})^2$.Hz]}
		Force (N_{rms})	Frequency (Hz)		
Cymbal (K. Uchino and T. Ishii, Ferroelectrics, 400, 305 (2010)	10.5	49.5	100	52	20.2
This TS-FAPEH	34	15	128	248	253

Resonance mode operation

Type of PEH	Weight (gram)	Excitation		Generated electrical power (mW)	Power density normalized by weight and accel.² [W/(kg.g²)]
		Acceleration (g_{rms})	Frequency (Hz)		
One-stage Flex tensional (O. Sosnicki, N. Lhermet, and F. Claeyssen, ACTUATOR 2006)	269	0.9	110	50	0.23
This TS-FAPEH	34	0.7	213	366	22

- Power density is more one order of magnitude higher than others

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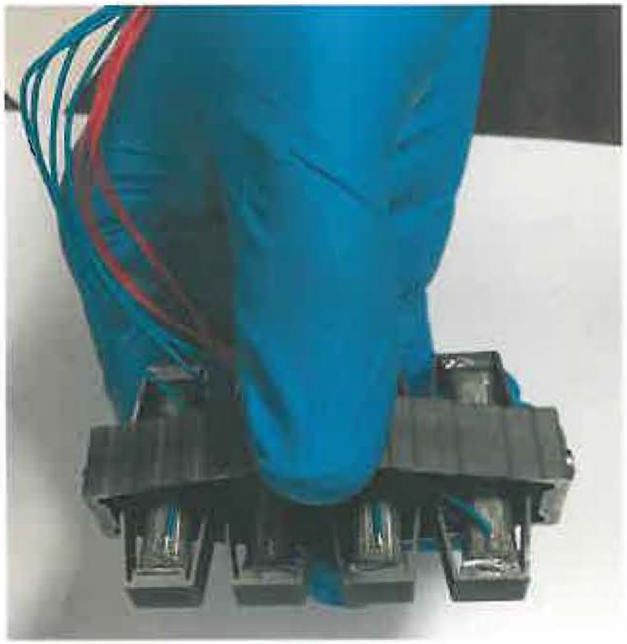
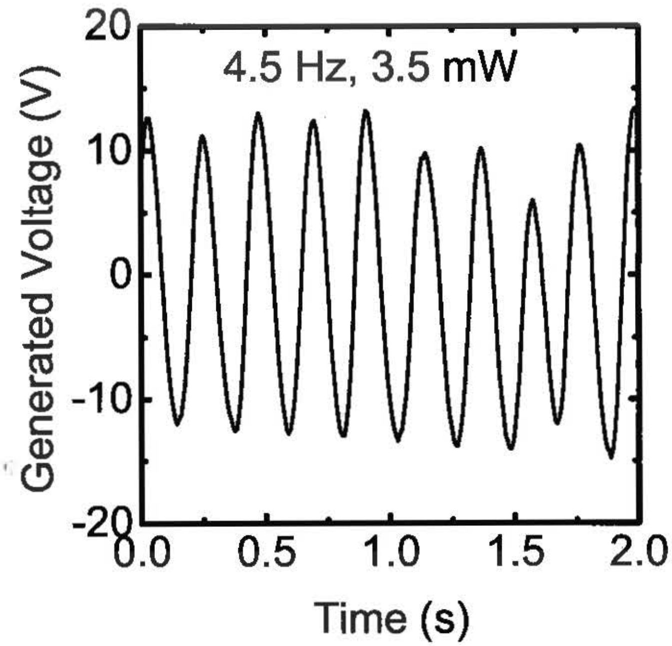
Low Cost PZT Polycrystalline Ceramic Stack-Based TS-FAPEH



Overall:
70 mm x 38 mm x 31 mm
Weight = 88 grams

PZT ceramic stack:
7 mm x7mm x 32.4 mm,
Weight = 9 grams
Capacitance = 2.5 μF

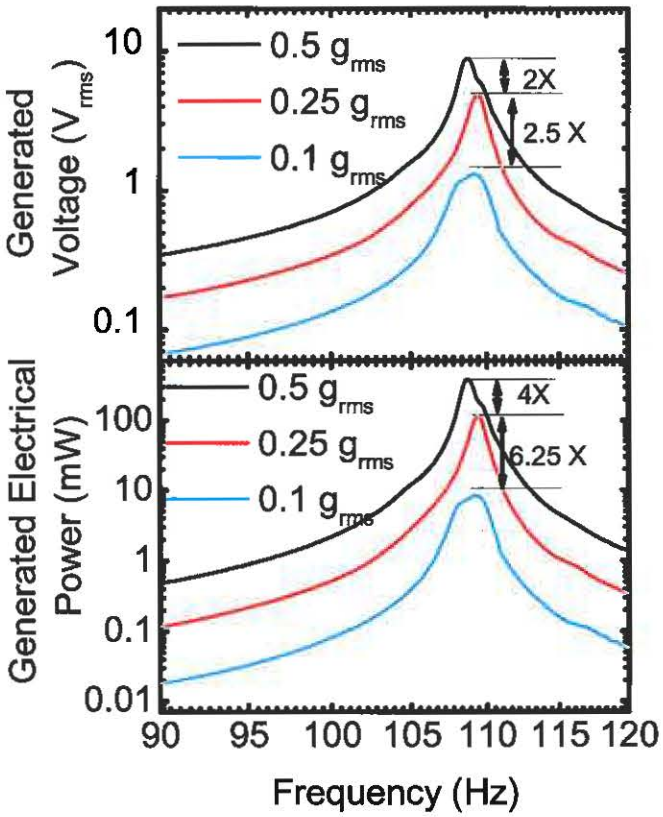


- Generated 3.5 mW electrical power from low frequency manual compression
- PZT polycrystalline material cost is 10 times lower than PMN-PT single crystal material

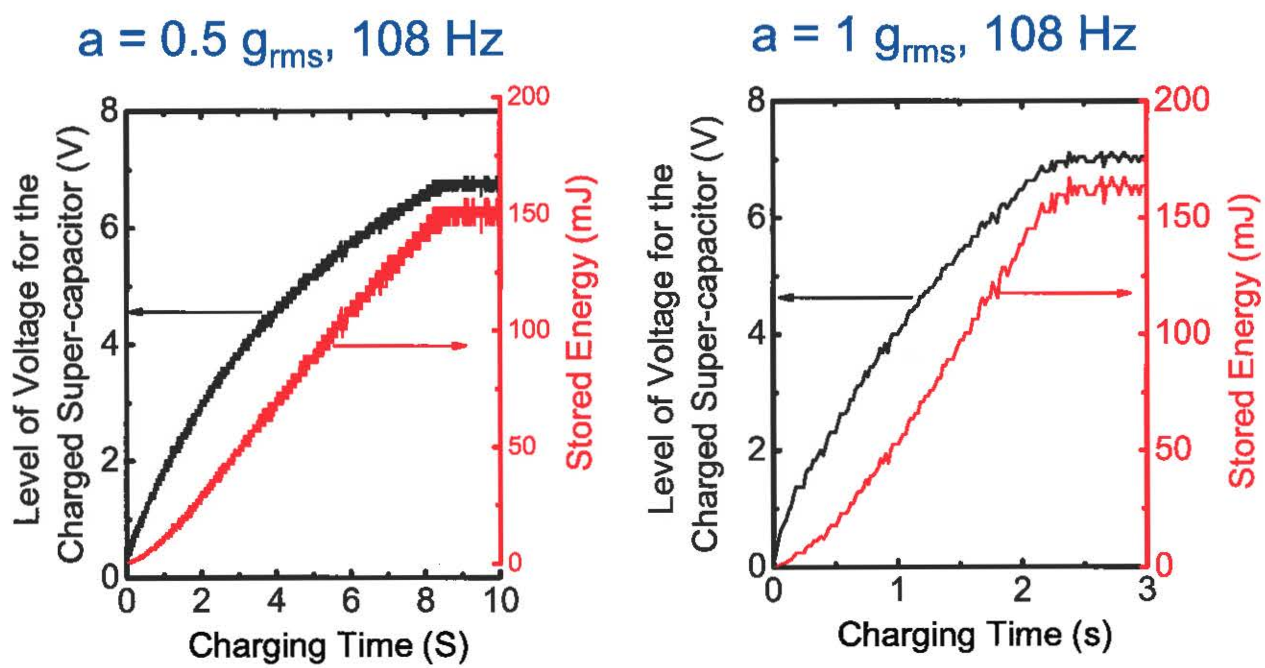
Resonance Mode Operation

PZT MS-FAPEH without Proof Mass

Frequency spectra



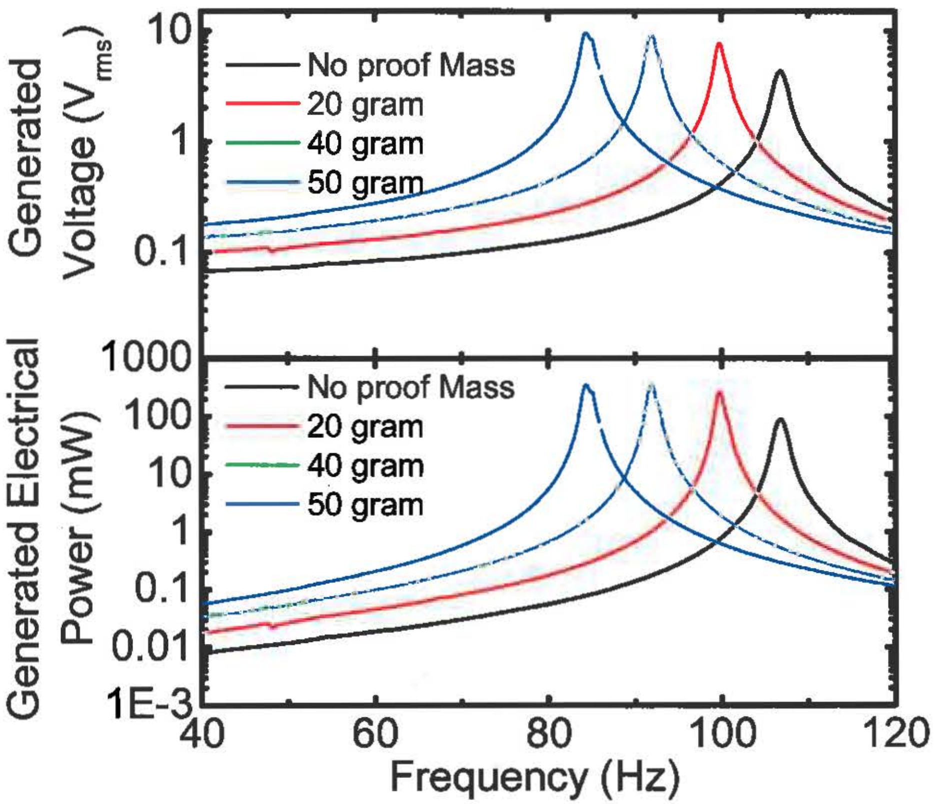
Charging a 6,600 μF Super-capacitor

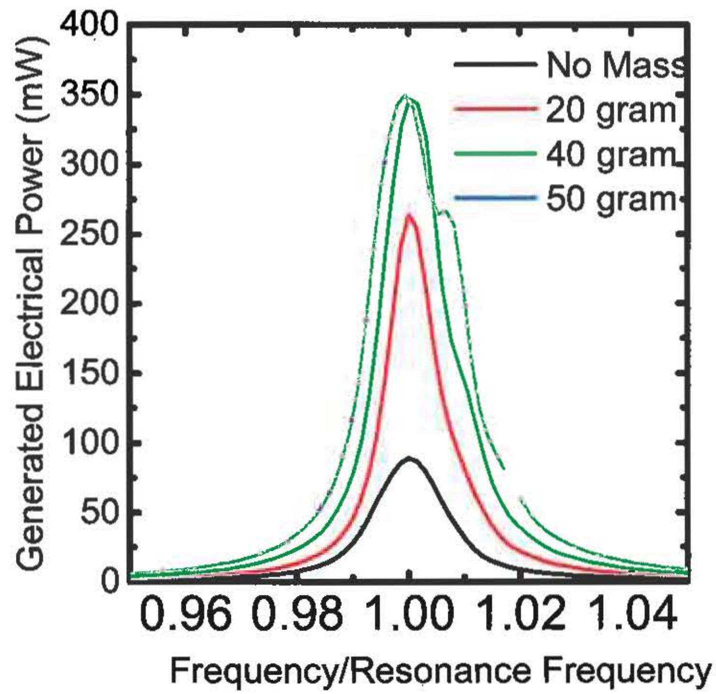


- It took 8 seconds to charge a 6,600 μF super-capacitor from 0 to 6.8 V (full) for 0.5 g_{rms} acceleration and 2 seconds for 1 g_{rms} acceleration.

Resonance Mode Operation

PZT TS-FAPEH with Proof Masses



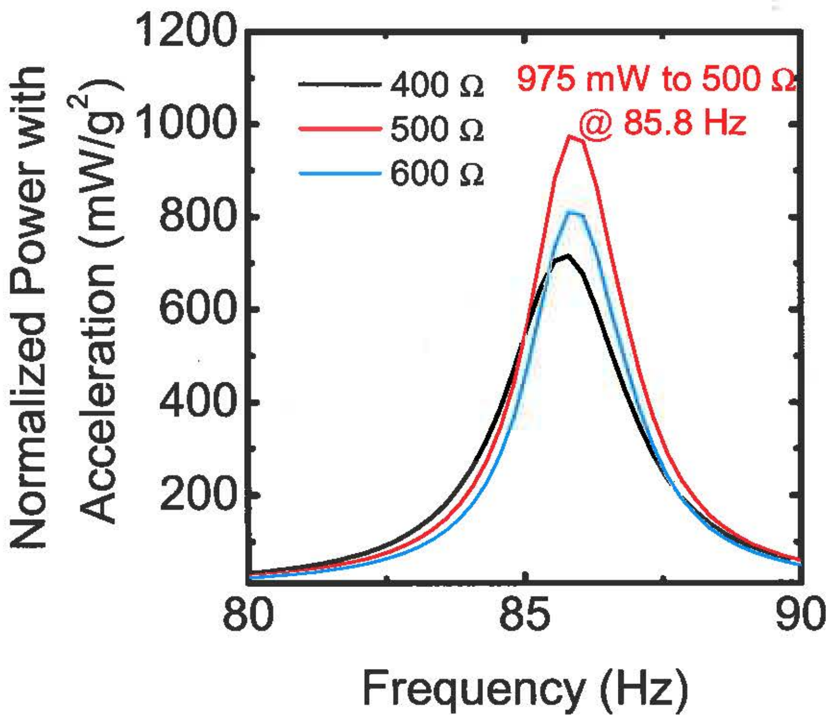


- Adding proof mass
  - Lowered the resonance frequency
  - Significantly increased the generated electrical power

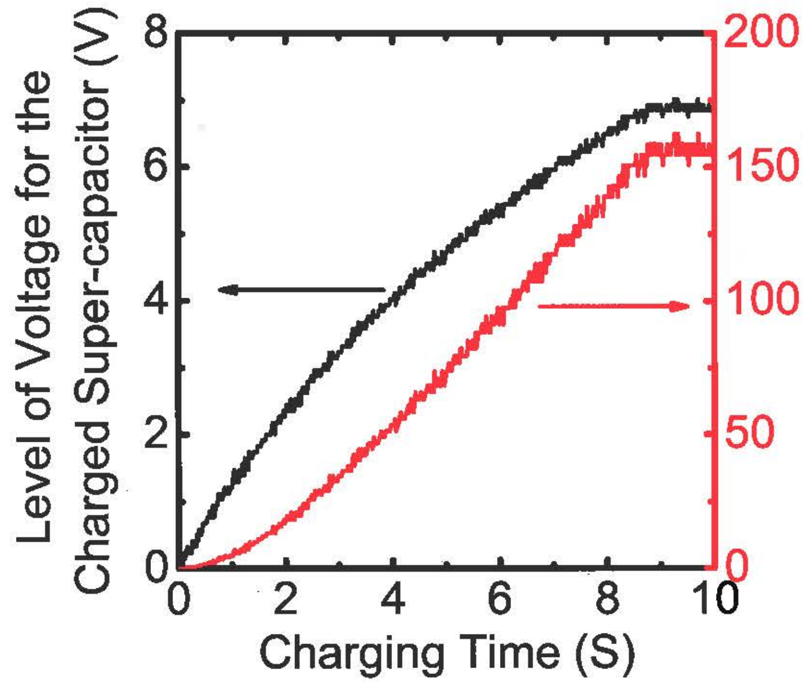
Resonance Mode Operation at 0.25 g_{rms} Acceleration

PZT TS-FAPEH with 50 gram Proof Mass

Power delivered to resistive loads



Charging a 6,600 μF Super-capacitor At 0.25 g_{rms} with 50 gram proof mass



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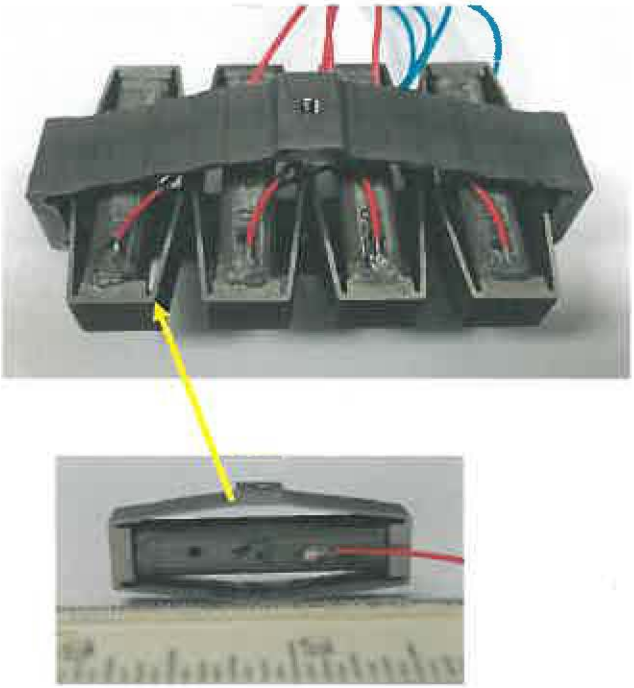
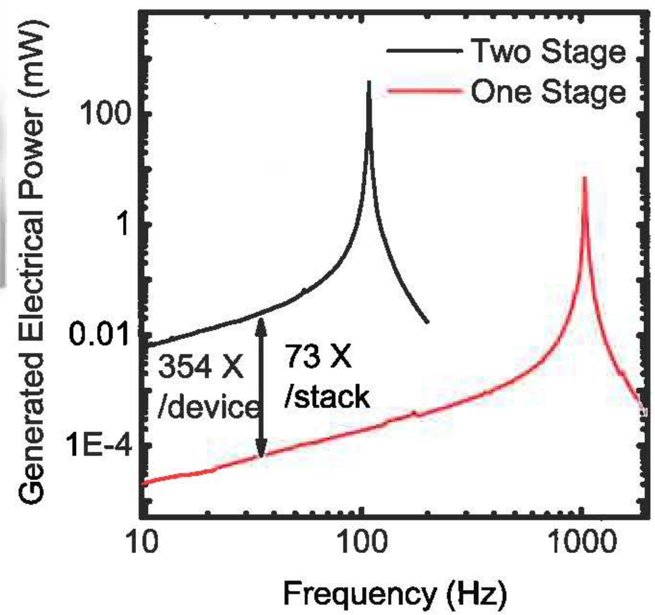
Comparison of Two-Stage and Single-Stage Flextensional Harvesters

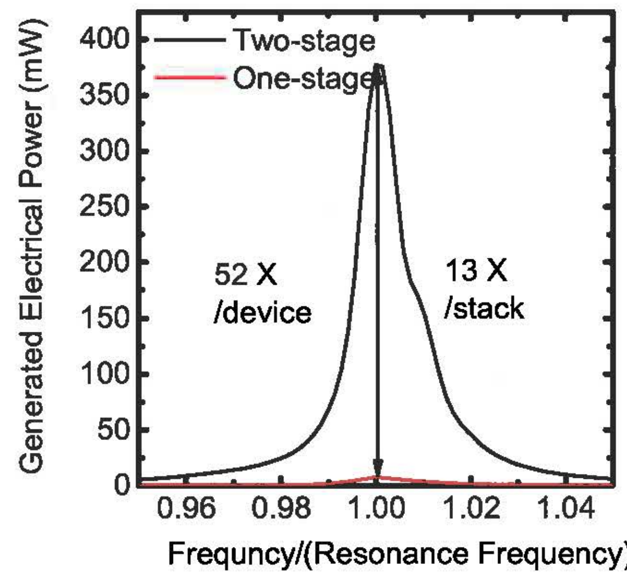
Two-stage



One-stage

At 0.5 g_{rms} acceleration





- The power density of the two-stage is more than one order of magnitude higher than the same-stacked one-stage
- The operational frequency of the TS-FAPEH is in the range of practical applications

Conclusions

- TS-FAPEH energy harvesters gave high energy (>10 times) density via three approaches:
  - *Two-stage structures* that capture orders of magnitude more mechanical energy
  - *"33" mode piezos* that increase energy conversion efficiency
  - *Optimized multilayer stacks* that increase energy storage efficiency many times
- The TS-FAPEH generated significantly higher electrical power both off-resonance and at resonance -- with and without proof masses
- A lower-cost PZT-multilayer TS-FAPEH also exhibits excellent performance
- The resonance frequency of the TS-FAPEH is in the range of many practical applications.

Contact Information

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- Questions?