Broadband Vibrational Energy Harvesting using Nonlinear Systems

D. Mallick, **S. Roy**

Tyndall National Institute
Cork, Ireland

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PSMA Inaugural International Energy Harvesting Workshop
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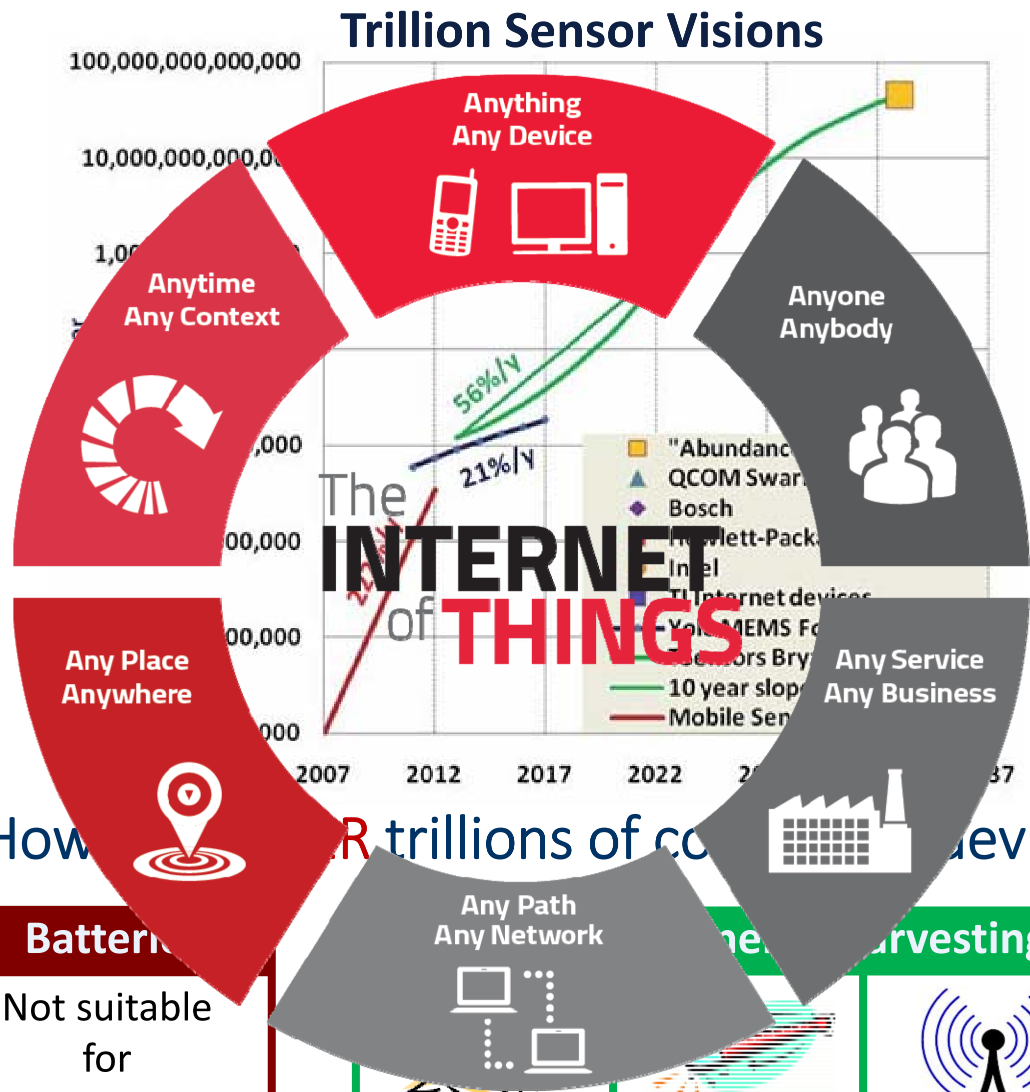
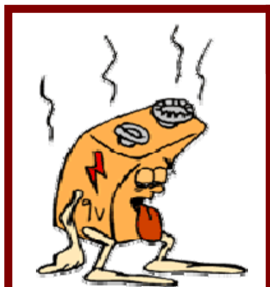
Internet of Things (IoT)
Wirelessly connecting Anything

Tyndall National Institute
Institiúid Náisiúnta



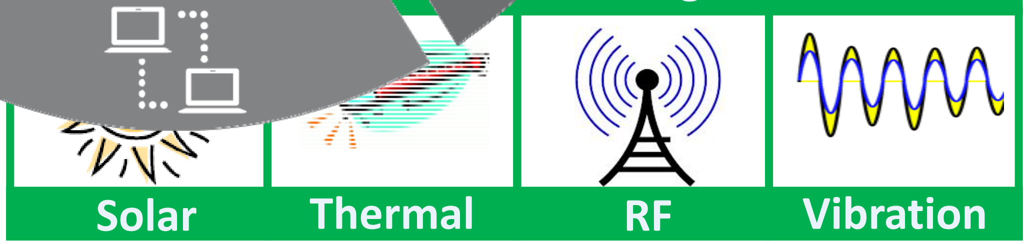
How R trillions of co devices?



Batteri

Not suitable for 'fit-and-forget' applications

ne rvesting



Mechanical Energy Harvesting

What releases mechanical energy – **Almost Anything**

- Online database – **Real Vibrations** - NiPS lab, University of Perugia, Italy.
  - **EH Networks Database** – EPSRC Funded Network.

- Vibration data from more than 600 sources comprising –
  - Human Activities
  - Machine
  - Automobile/Aerospace
  - Large Structures

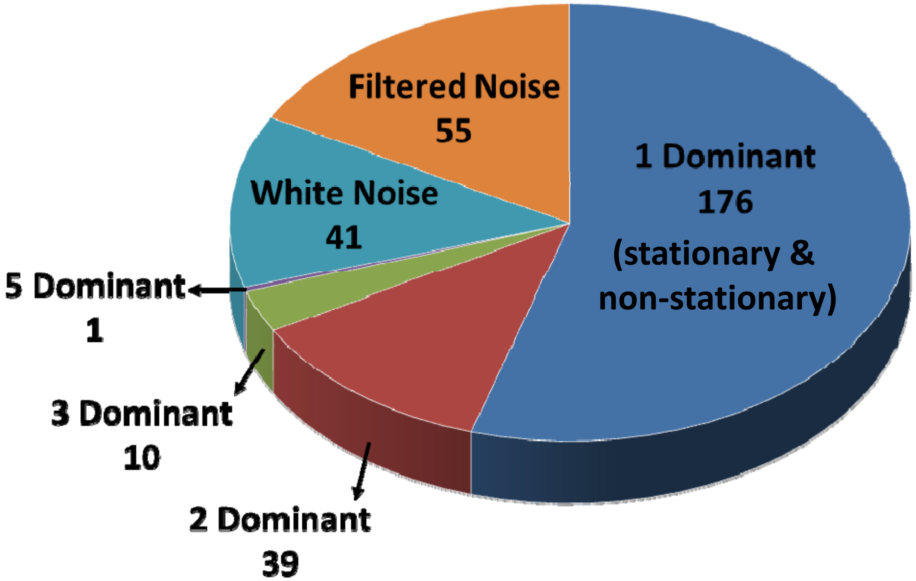
- **Neri et al., J. Intell. Mat. Syst. Struc., 23.18 (2012): 2095-2101.**
- **http://eh-network.org/data/**

Mechanical Energy Harvesting

What releases mechanical energy – Almost Anything



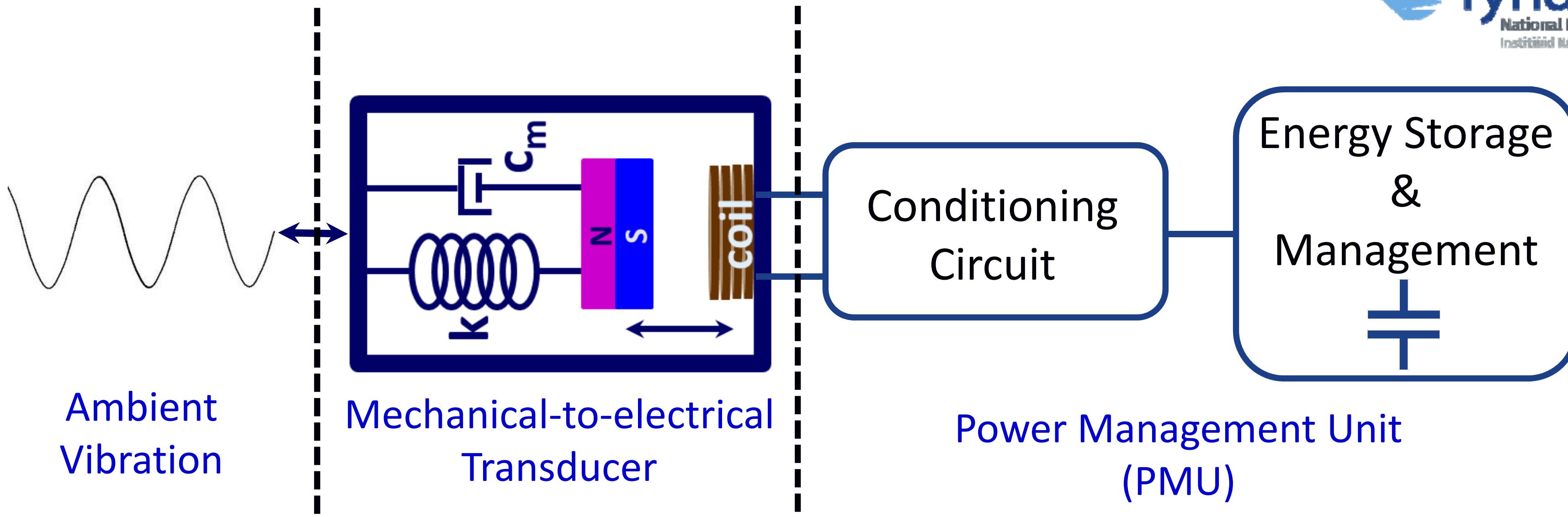




- 23% Sources – single dominant, stationary frequency.
- 53% Sources contains –
  - ❖ single dominant, non-stationary frequency
  - ❖ multiple dominant, stationary frequencies
  - ❖ white/filtered noise - broadband

R. Rantz & S. Roundy, SPIE SSMNEHM, International Society for Optics and Photonics, 2016.

Inertial Energy Harvesting System



Second Order Spring Mass Damper System

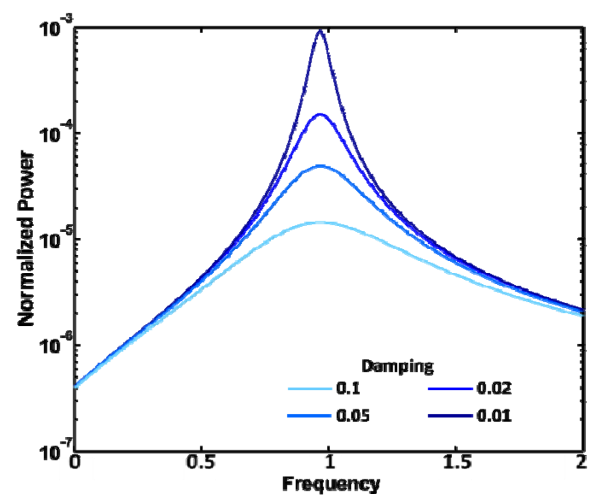
$$m\ddot{x}(t) + (c_m + c_e)\dot{x}(t) + kx(t) = -m\ddot{y}(t)$$

Power dissipated in the electrical damper

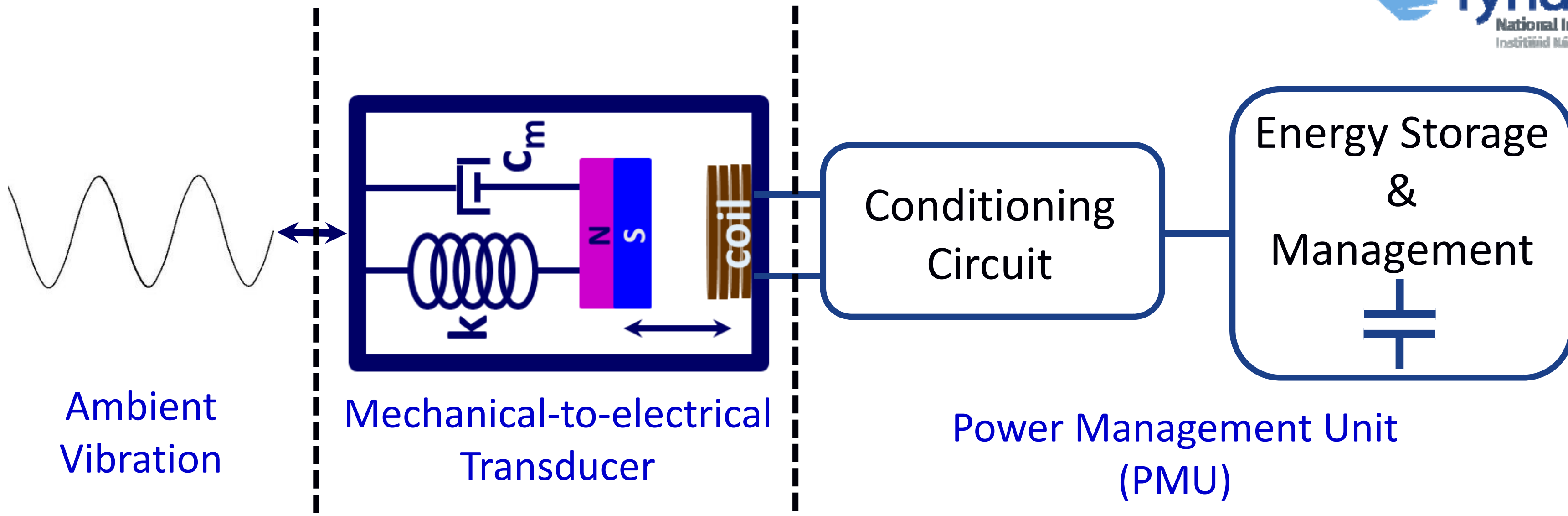
$$P_{elec} = \frac{c_e\left(\frac{\omega}{\omega_n}\right)^3 {Y_0}^2 \omega^3}{2\omega_n\left[\left\{2\rho_T\left(\frac{\omega}{\omega_n}\right)\right\}^2 + \left\{1 - \left(\frac{\omega}{\omega_n}\right)^2\right\}^2\right]}$$

At Resonance:

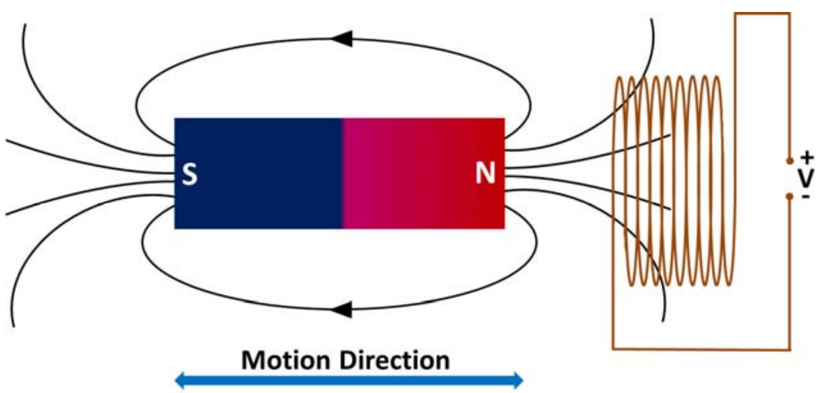
$$P_{elec}\big|_{\omega=\omega_n} = \frac{c_e m^2 {Y_0}^2 {\omega_n}^4}{2(c_m + c_e)^2}$$



Inertial Energy Harvesting System



Principle governing EM generators is Faraday's Law



$$\textbf{EMF (V)} = -N\frac{d\Phi}{dt}$$

Induced voltage $V_o = Z_{max}\omega_n N\frac{d\Phi}{dz}$

Load Voltage $V_L = V_o\frac{R_L}{(R_L+R_C)}$

Power delivered to load $P_L = \frac{{V_L}^2}{2R_L}$

Wideband Energy Harvesting

Target: Wideband Operation

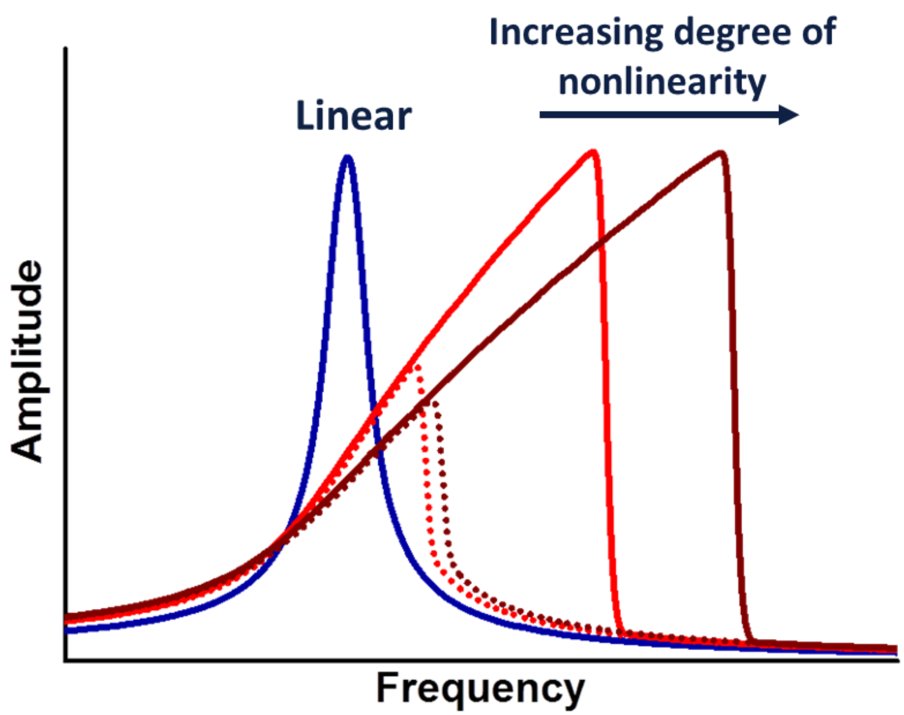
Linear → **Nonlinear**

Equation of motion of simplest energy harvesting systems

$$m\ddot{x}(t) + (c_m + c_e)\dot{x}(t) + F(x) = -m\ddot{y}(t)$$

Linear	$F(x) = kx$

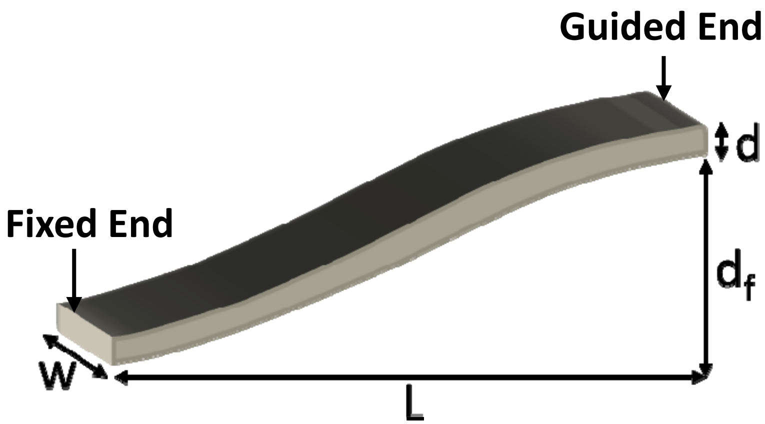
Nonlinear	$F(x) = kx + k_n x^3$



- Nonlinearity through stiffness
- Increase in Bandwidth
- No tuning needed; No array of devices needed
- Gain in output power
  $$\frac{P_{nonlinear}}{P_{linear}} \leq \frac{4}{\pi}$$

Analysis of Nonlinear Stretching

Clamped Guided MEMS beam:

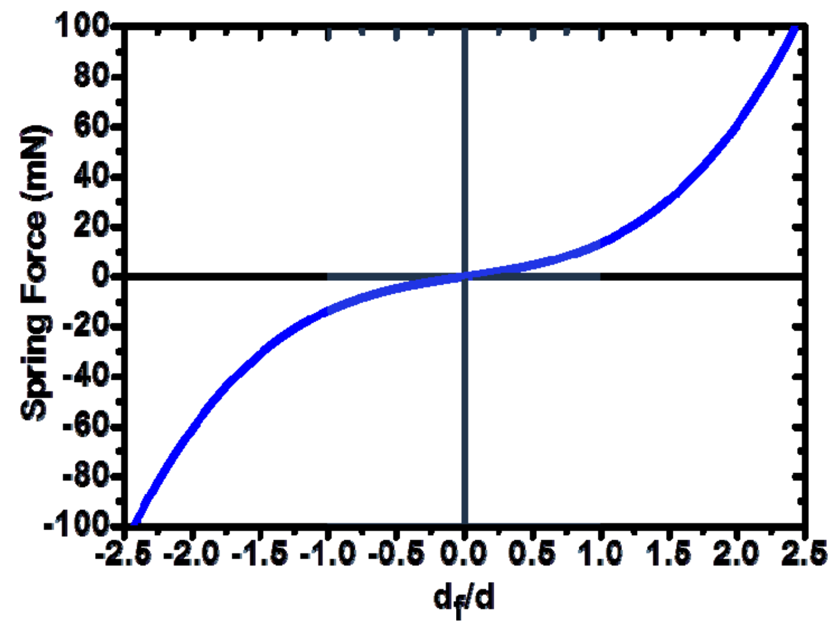


Total spring reaction force:

$$F = F_b + F_s = -\frac{Y}{L^3} W d^4 [\frac{d_f}{d} + \boxed{\frac{18}{25}\left(\frac{d_f}{d}\right)^3}]$$

Bending Force — Stretching Force — Cubic Nonlinearity

- $\frac{d_f}{d}$ << 1 - nonlinearity is insignificant
- $\frac{d_f}{d} \geq 1$ – cubic nonlinearity is significant



linear stiffness constant: $\boldsymbol{k = \frac{YWd^3}{L^3}}$ nonlinear stiffness constant: $\boldsymbol{k_n = \frac{18YWd}{25L^3}}$

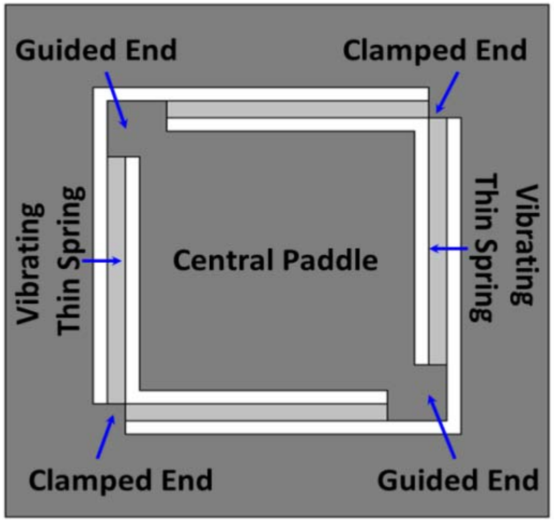
$$\boldsymbol{\frac{k_n}{k} = \frac{18}{25d^2}}$$

Smaller the thickness, larger the nonlinearity

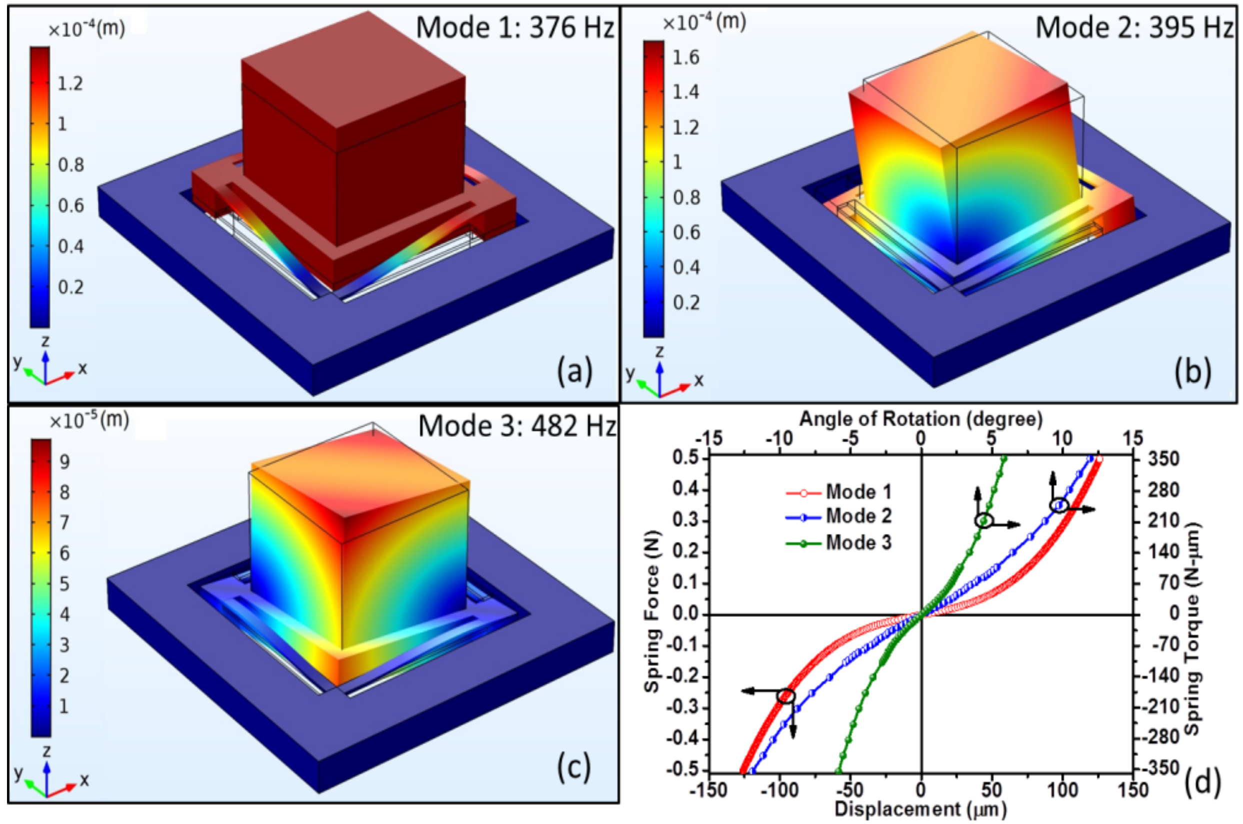
D. Mallick et al, Smart Mater. Struct., 24, 015013 (2015).

MEMS Nonlinear Wideband Operation

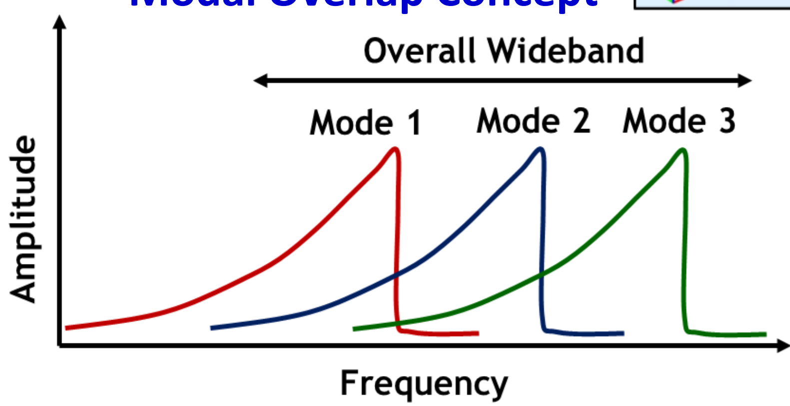
Design of the Nonlinear Architecture



FEM Simulation



Modal Overlap Concept

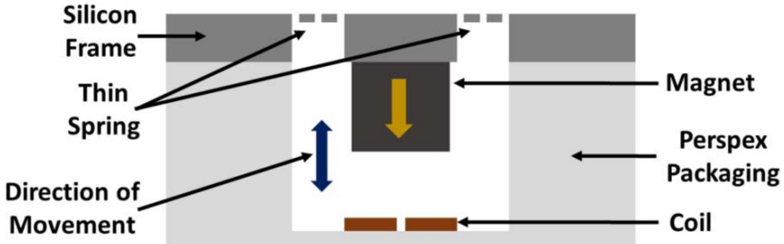


- Nonlinear effect observed in first 3 modes
- Closely spaced mode overlap in frequency response

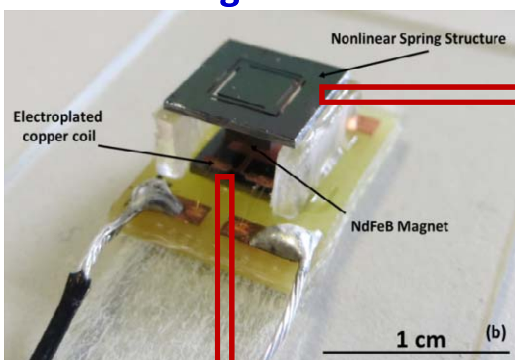
D. Mallick et al., Journ. Microelectromech. Syst., 26(1): 273-282 (2017).

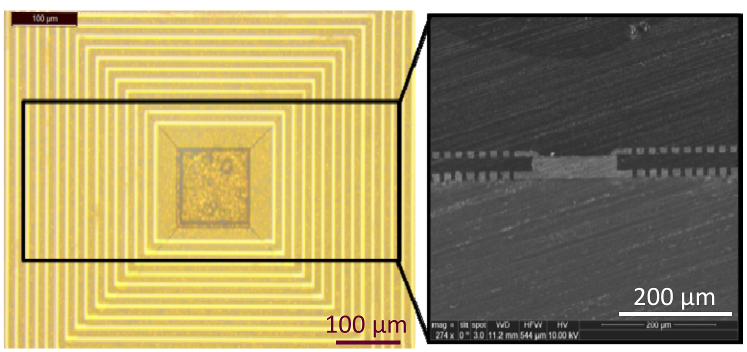
Device Fabrication and Testing

Device Schematic Cross-section



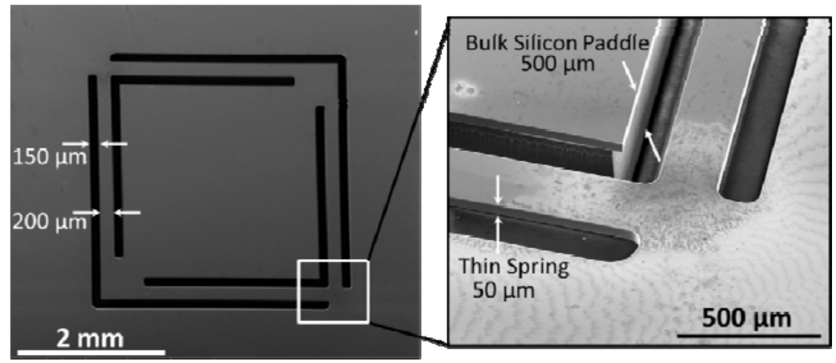
Packaged Device



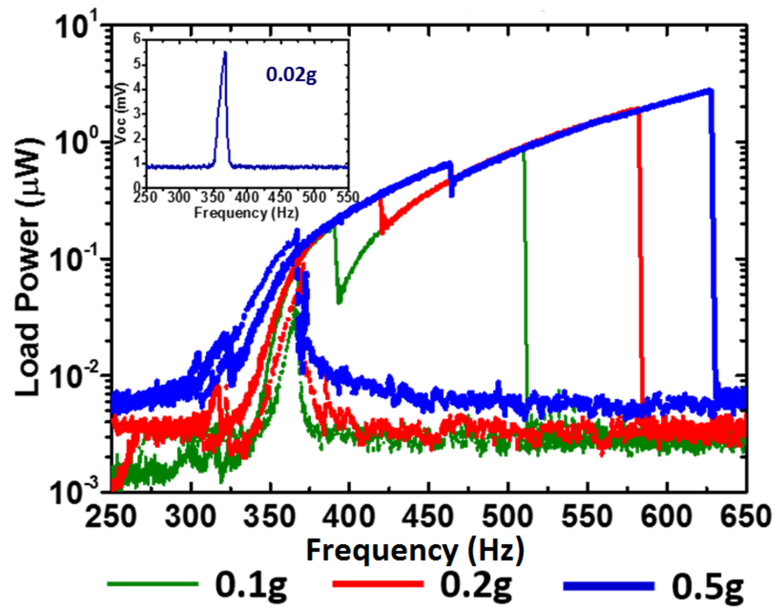


Electroplated Double Layer Copper Coil

ICP- DRIE etched SOI spring structure



Load Power vs Frequency Response

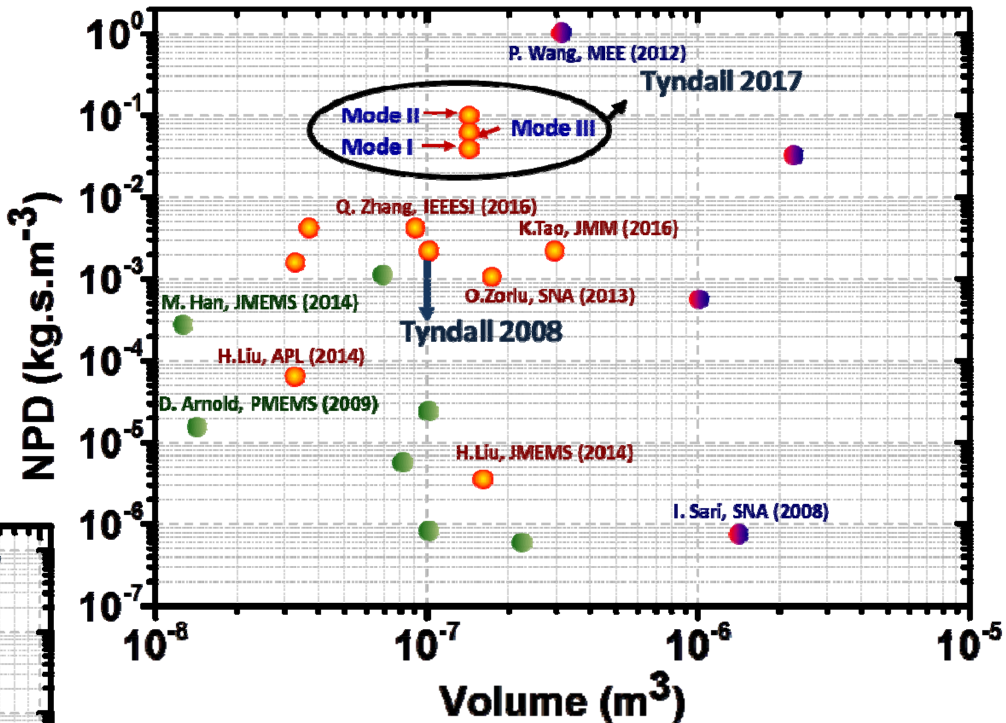


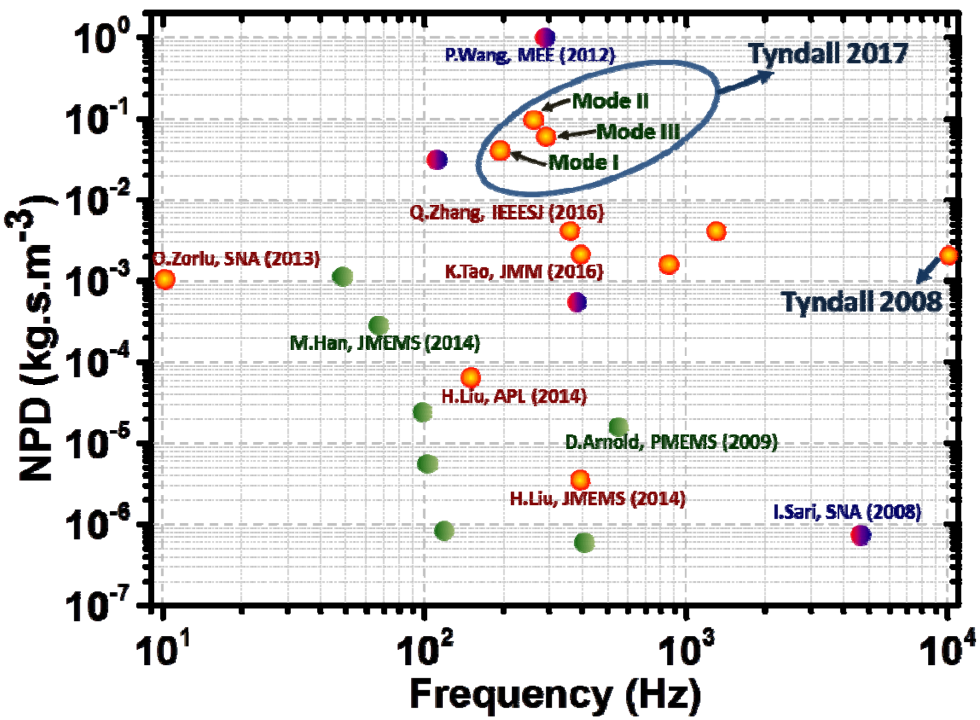
- Bandwidth – 82 Hz @ 0.5g with 2.8 µW

D. Mallick et al., Journ. Microelectromech. Syst., 26(1): 273-282 (2017).

Benchmarking the MEMS EM VEH

$$\text{Normalized Power Density(NPD)} = \frac{\text{Power}}{\text{Acceleration}^2.\text{Volume}}$$





- MEMS Suspension only
- MEMS Suspension with micro-coil
- Fully MEMS integrated

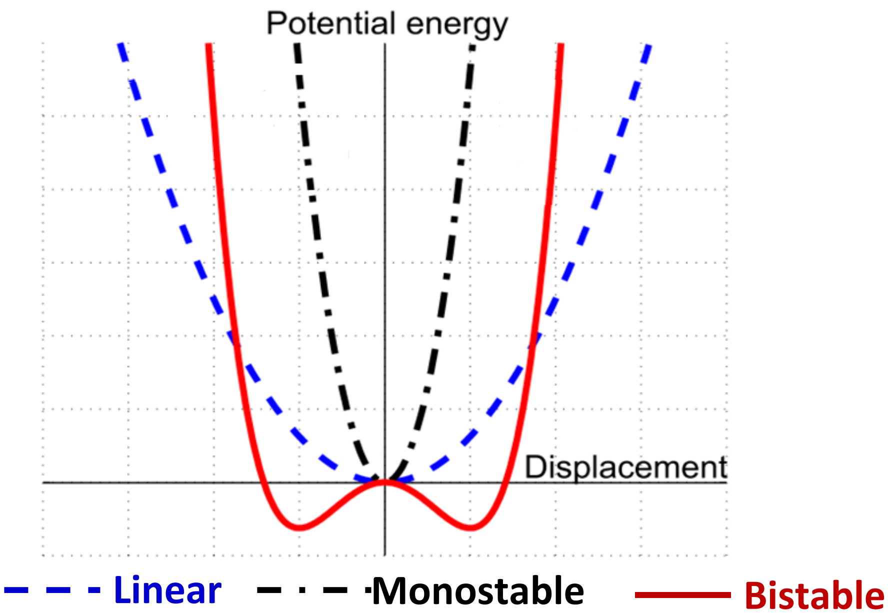
D. Mallick et al., Sens. Act. A: Phys., 264, 247 (2017)

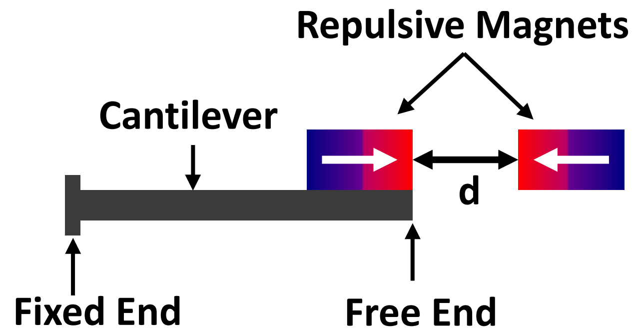
Bistable Energy Harvesting

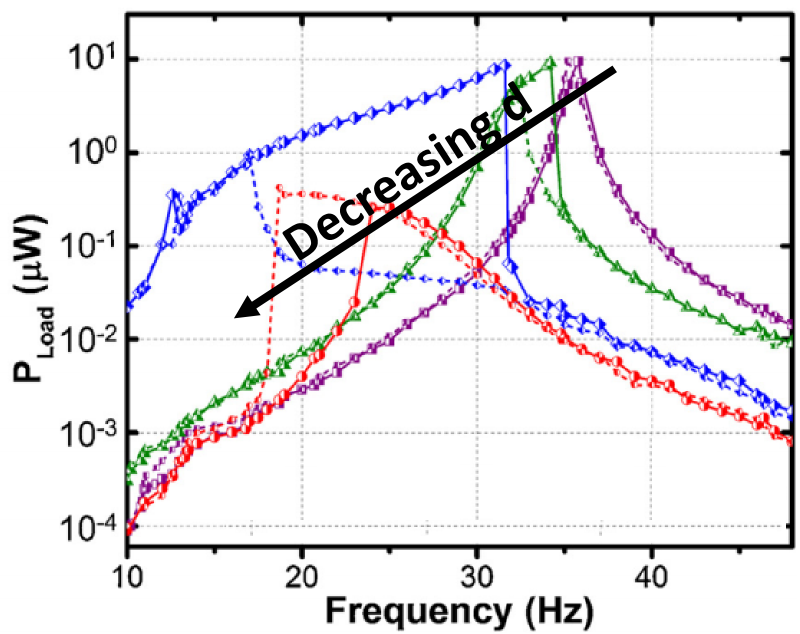
Potential Energy:

$$U(x) = \frac{1}{2}kx^2 + \frac{1}{4}k_n x^4$$

- $k_n = 0, k > 0$: linear
- $k_n > 0, k > 0$: monostable
- $k_n > 0, k < 0$: bistable



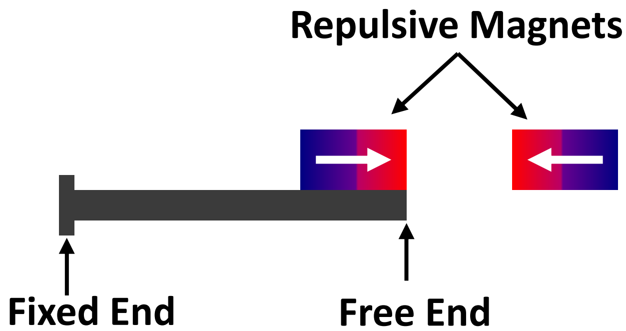




- Magnetic repulsive force creates bistable potential
- Intra-well oscillation – monostable like behaviour
- Inter-well oscillation – more interesting

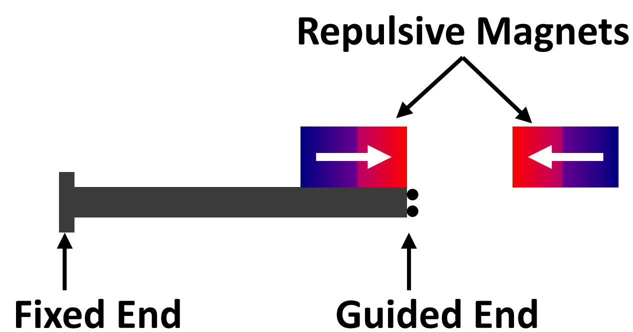
P. Podder et al., Sens. Act. A:Phys., 227, 39-47 (2015)

Effect of Fundamental Potentials



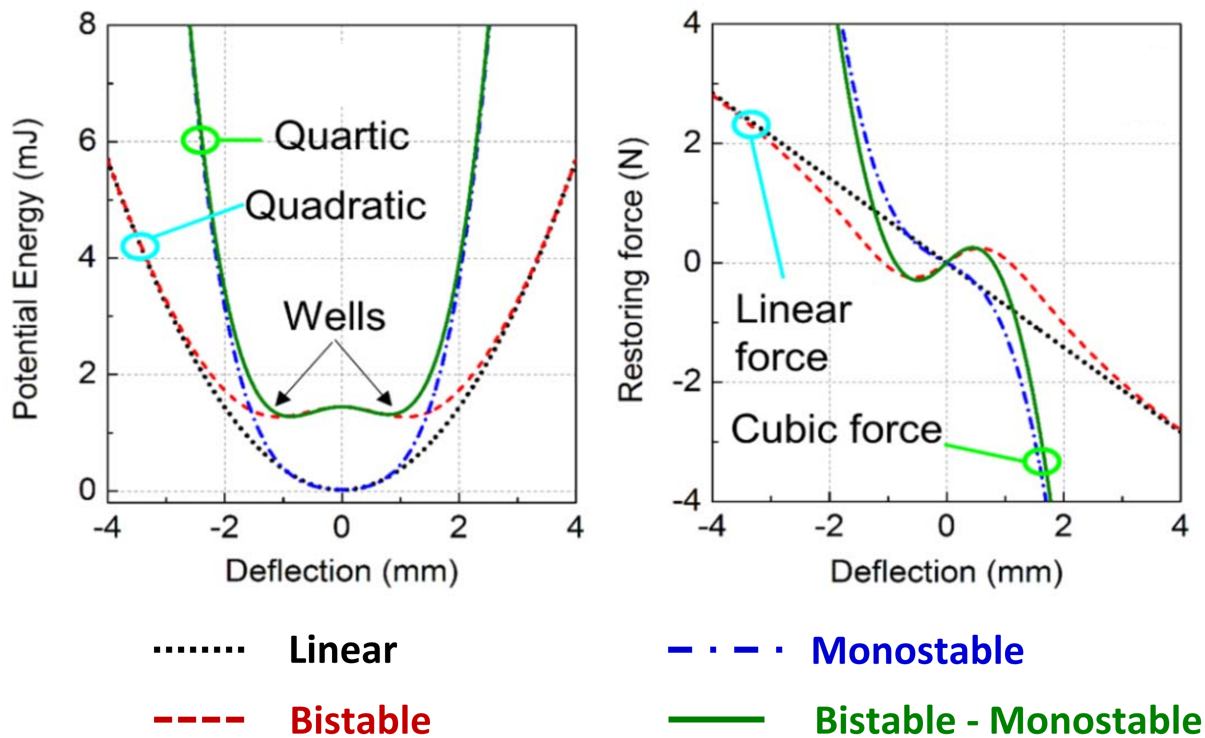
Linear Beam – Quadratic Potential

$$U(x) = \frac{1}{2}kx^2$$



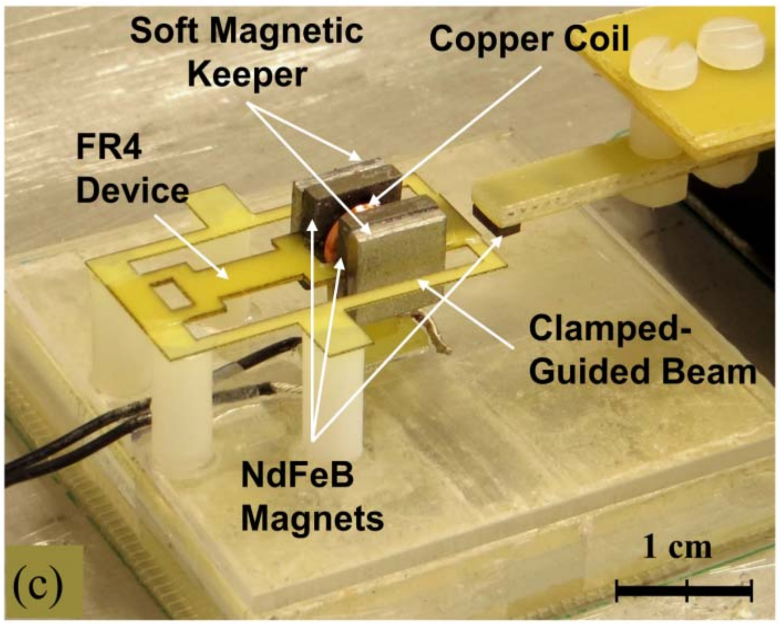
Nonlinear Beam – Quartic Potential

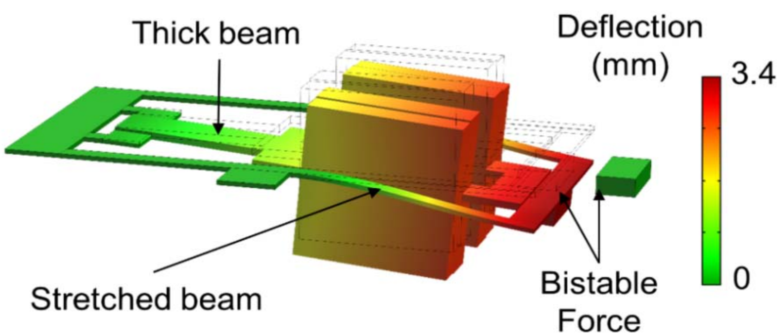
$$U(x) = \frac{1}{2}kx^2 + \frac{1}{4}k_n x^4$$

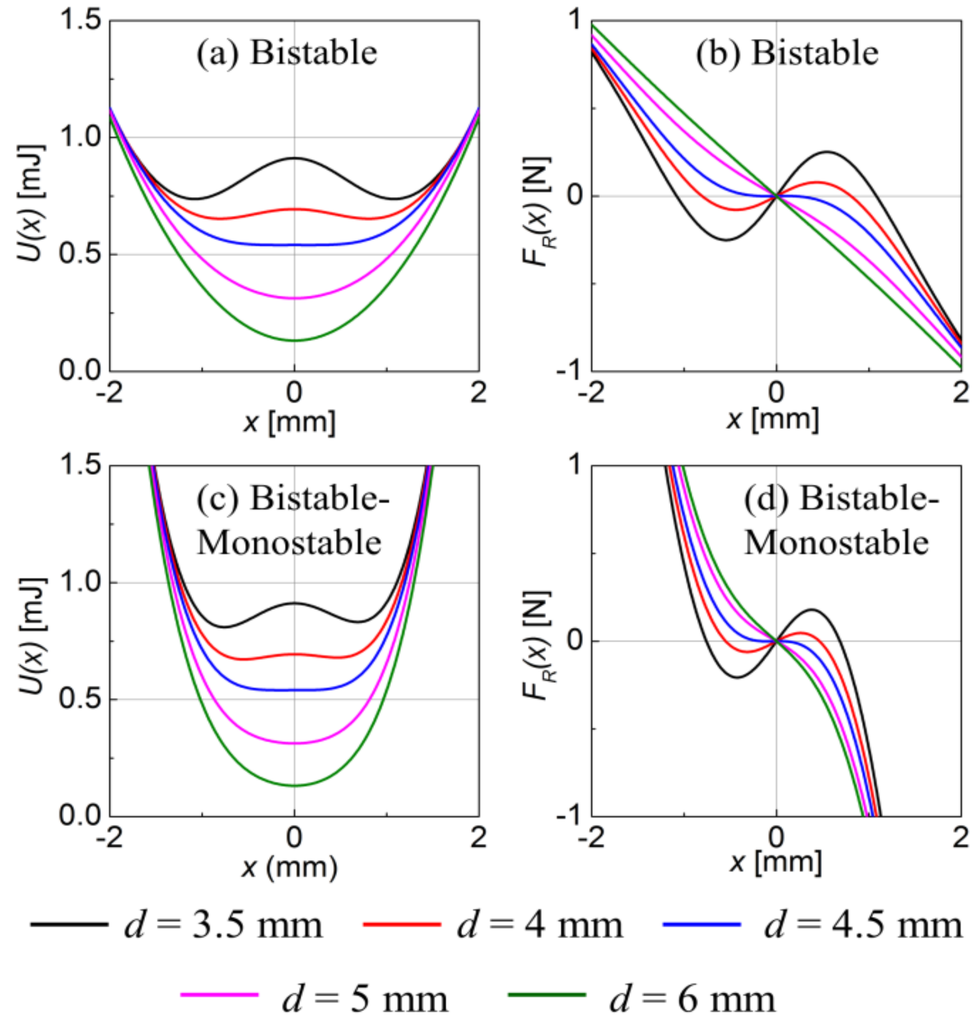


P. Podder et al., Sci. Rep. (Nature), 6, 37292 (2016)

Combined Multiple Nonlinearity





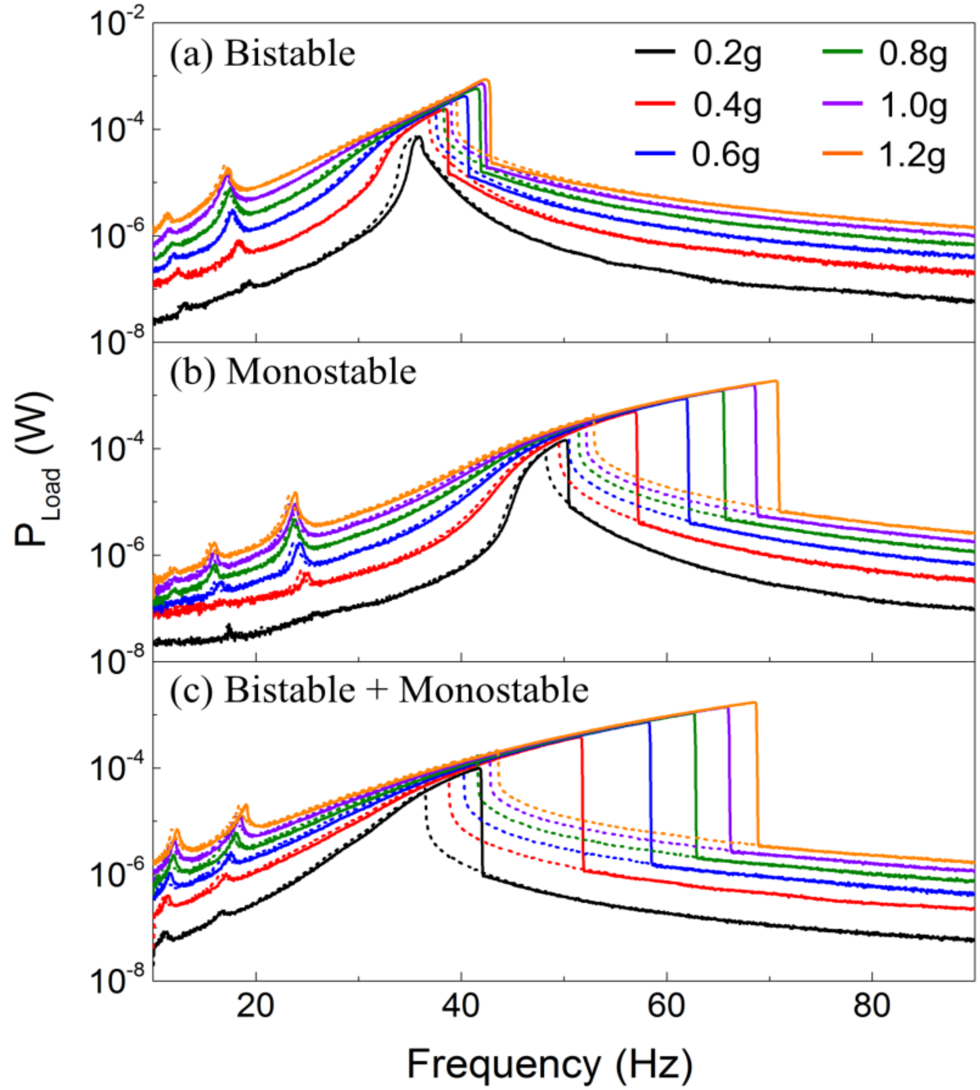


- **Monostable and Bistable nonlinearity combined in a single device**
- **Engineered potential energy for better performance**

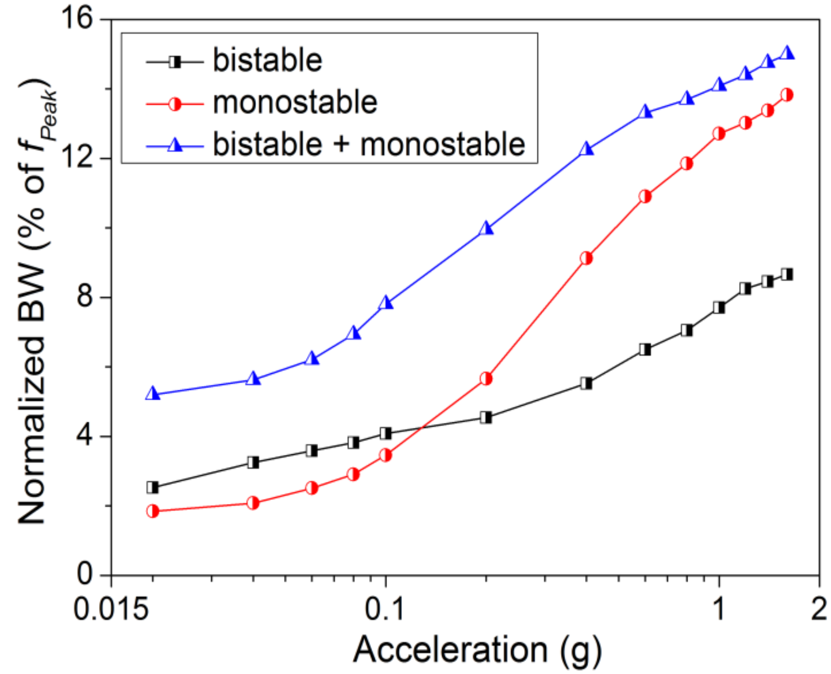
P. Podder et al., Sci. Rep. (Nature), 6, 37292 (2016)

Combined Multiple Nonlinearity (II)

Load Power vs Frequency Responses:



Normalized Bandwidth variation:

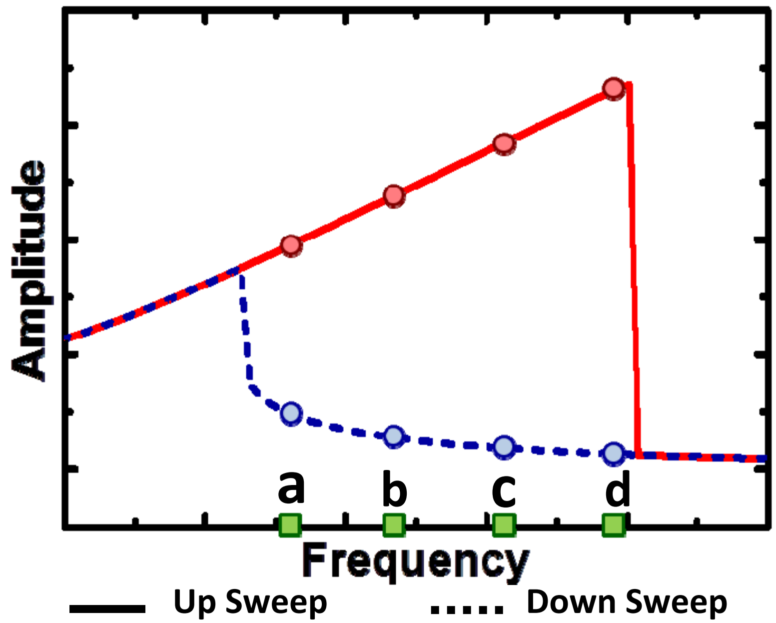


- **Improvement in the low frequency region**
- **Two times Bandwidth compared to individual mono/bistable systems**
- **Major advantage in low acceleration applications**

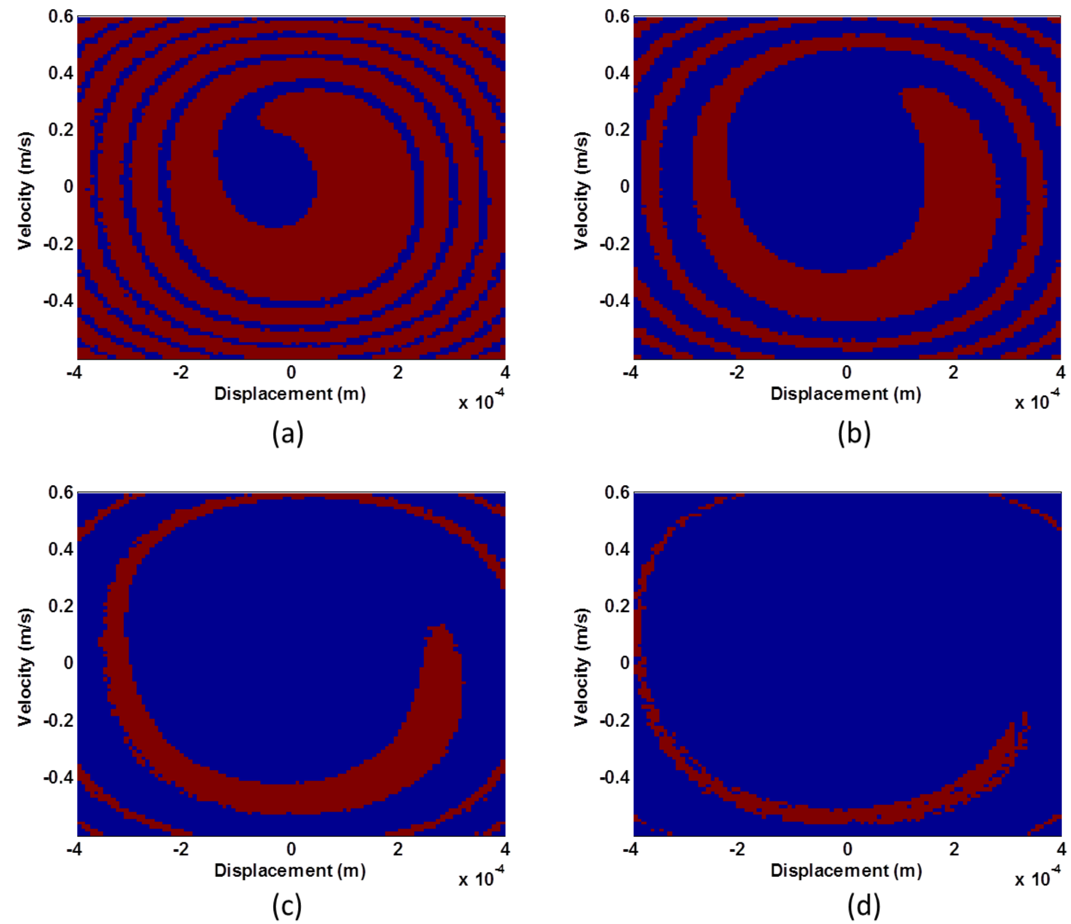
P. Podder et al., Sci. Rep. (Nature), 6, 37292 (2016)

Nonlinear Hysteresis

Frequency Domain Response



Basin of Attraction Plots within Hysteresis



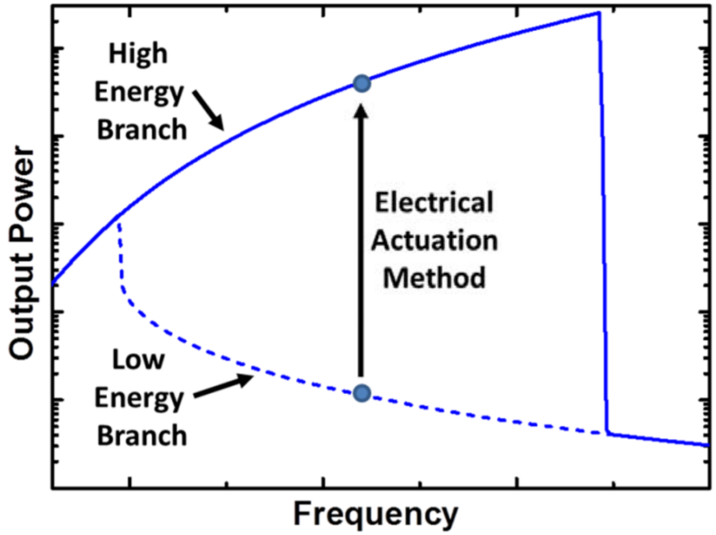
Blue – Low Energy Red – High Energy

- Multiple steady state solutions - Hysteresis
- How to operate in the frequency varying environment?

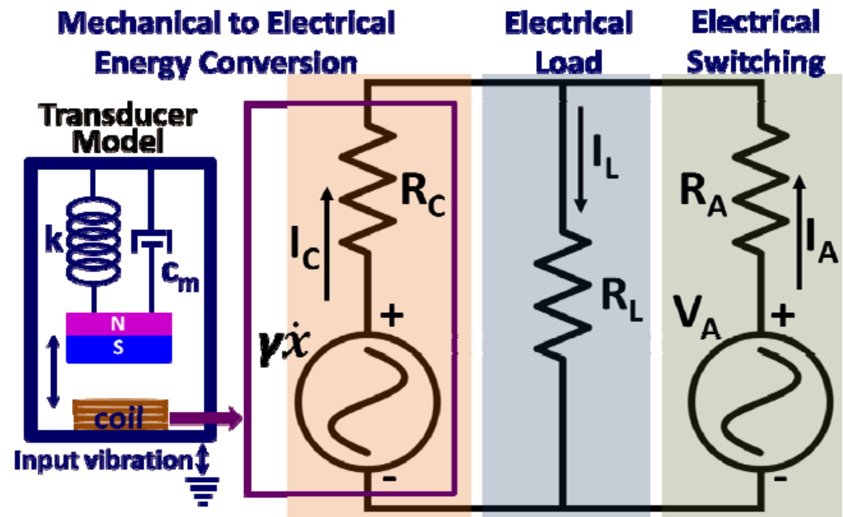
D. Mallick et al, Smart Mater. Struct., 24, 015013 (2015).

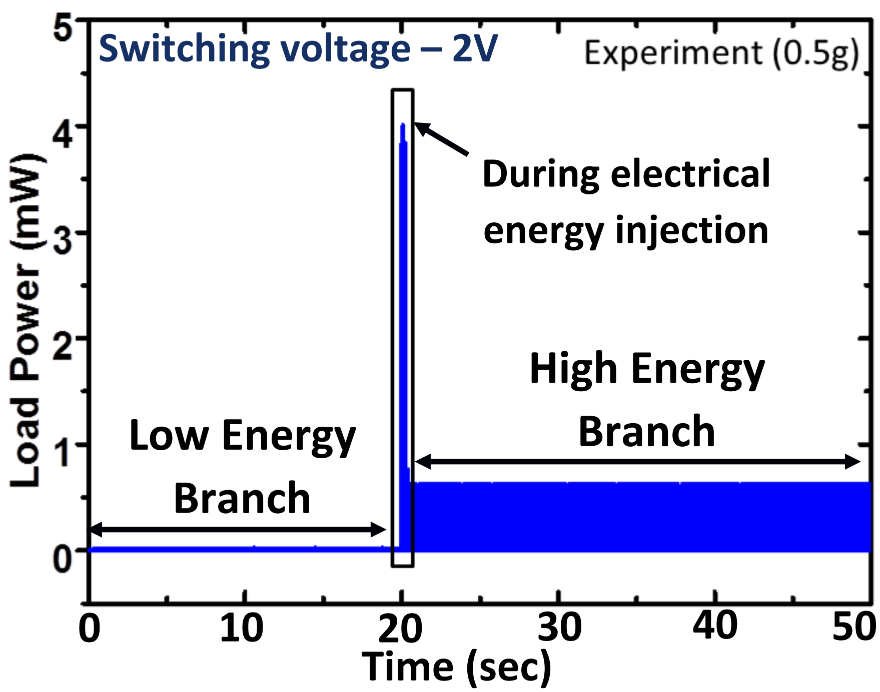
Surfing the High Energy Branch (I)

Concept



Implementation



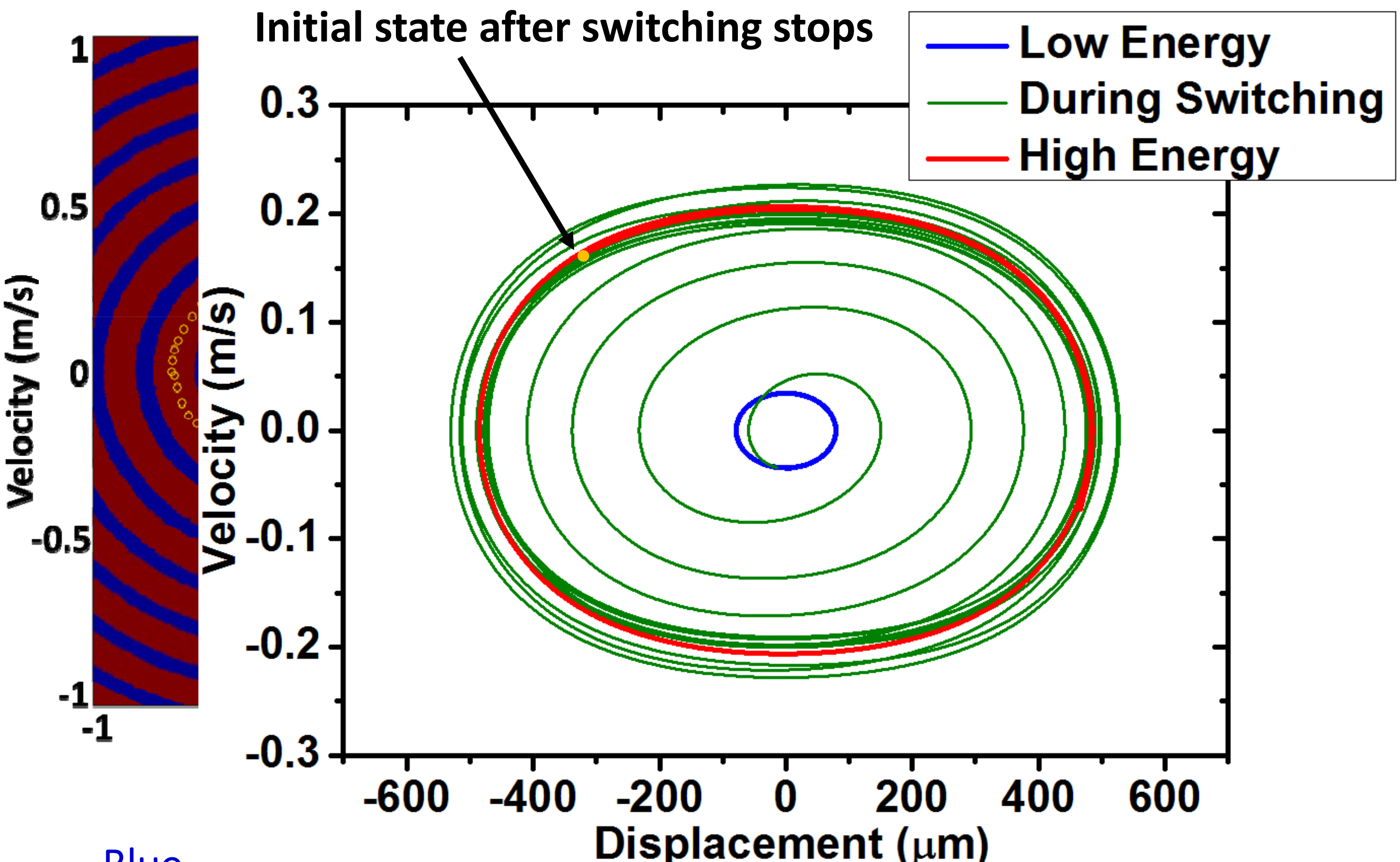


- Injected energy switches the state from actual to desired attractor
- Maintains steady state – without continuous energy input

D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Successful/Unsuccessful Switching

Phase Space Diagram



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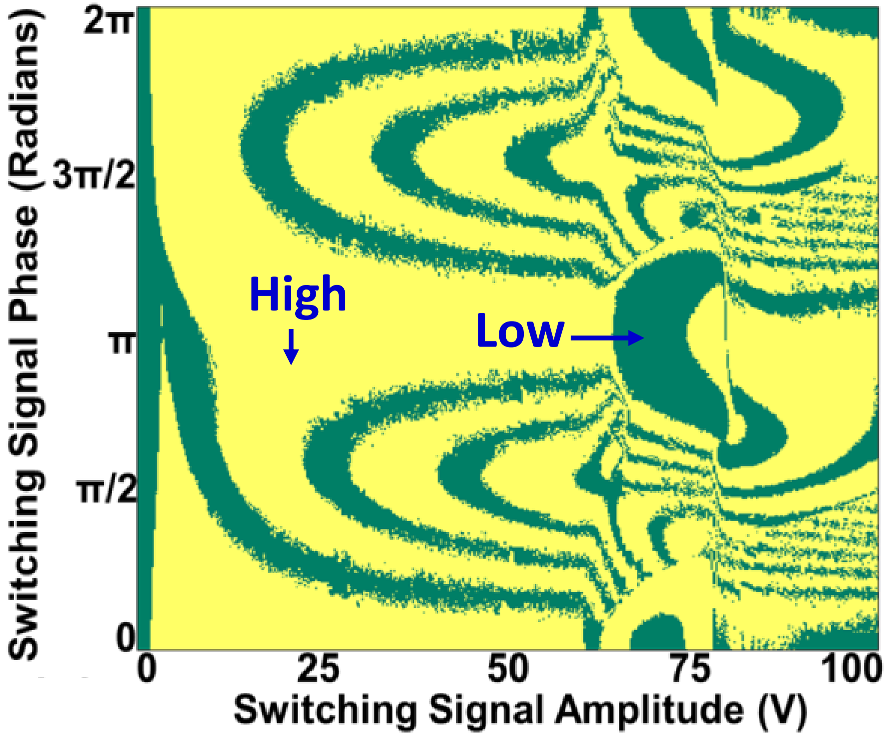
mplitudes

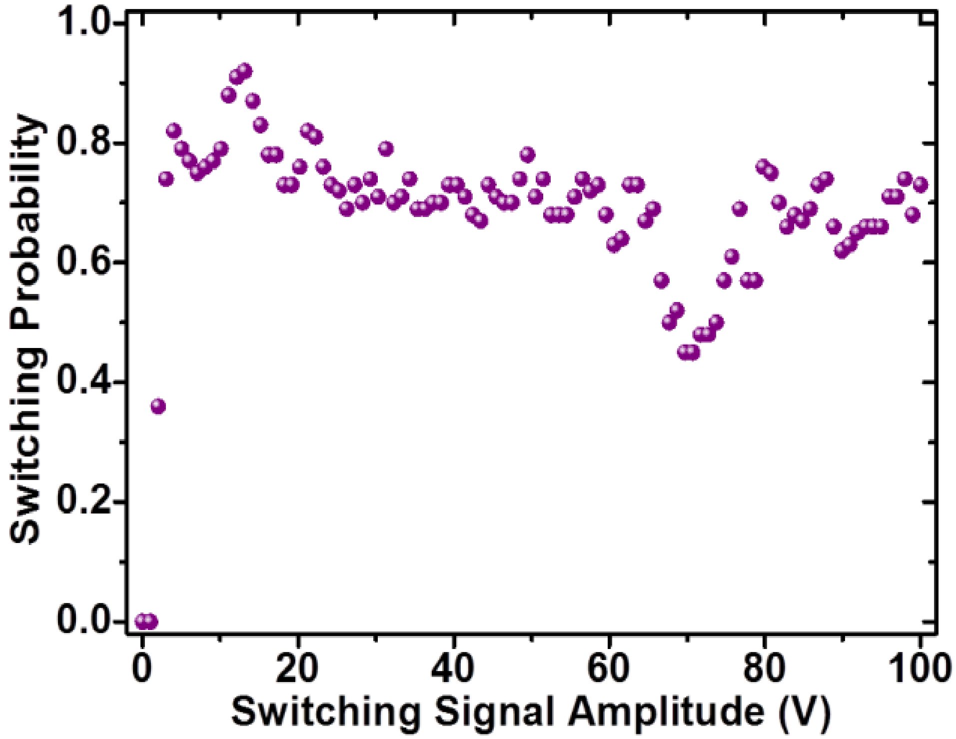
Blue -

D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Surfing the High Energy Branch (II)

Probabilistic Study on Switching Mechanism

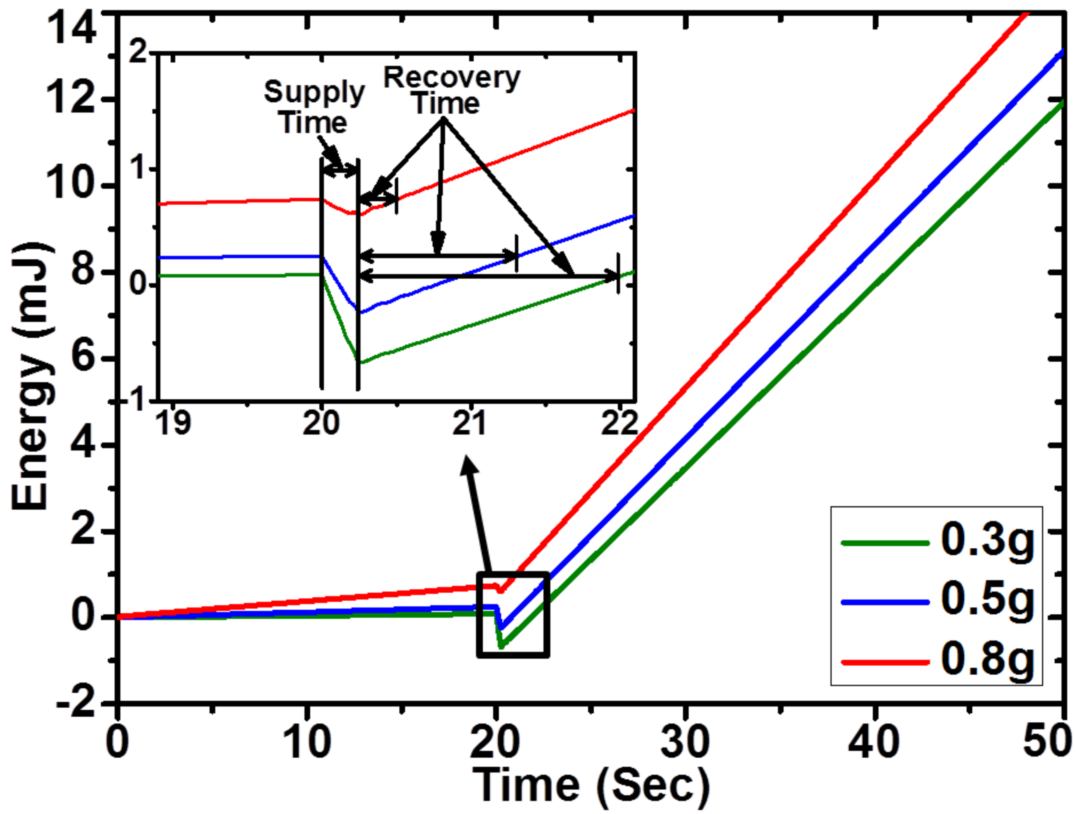




D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Surfing the High Energy Branch (III)

Evolution of Net Electrical Energy



E_0 - Energy to apply switching signal once

P_S - Probability of successful switching in first attempt

E_T - Total energy spent to switch the state

k - Number of attempts

$$E_T = P_S E_0 \sum_{k=1}^{\infty} k(1 - P_S)^{k-1} = \frac{E_0}{P_S}$$

As P_S ~ 0.8, E_T - not very high

D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Remarks

Conclusions:

- **Stretching nonlinearity** with modal overlap – ideal for MEMS VEH devices
- **Bistable-Monostable VEH** combines the beneficial features of bistable and monostable nonlinearities, and delivers better spectral response than both.
- **Multi stability** – major challenge in nonlinear oscillator based applications
- **Switching mechanism in nonlinear VEH –** Huge improvement energy conversion efficiency in a real application environment.
- **Switching mechanism** - independent of device scale or transduction methods

Future Work:

- **Automatize the Switching:** Self-controlled feedback loop development along with the power management circuit

Acknowledgement:

SFI PI grant award (2012)- MEMS vibrational energy harvesting – 11/PI/1201

People involved in this work:

Dr. Andreas Amann

Dr. Pranay Podder

Dr. Peter Constantinou

Ms. Kankana Paul

Tyndall - Speciality Products & Service (SP&S) group

Thank You

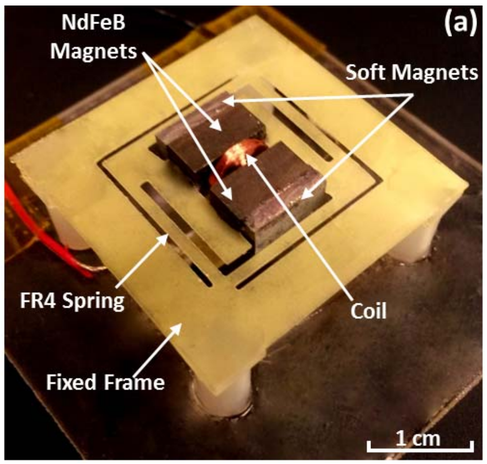
Contact: dhiman.mallick@tyndall.ie

Low Frequency Operation (Meso-scale)

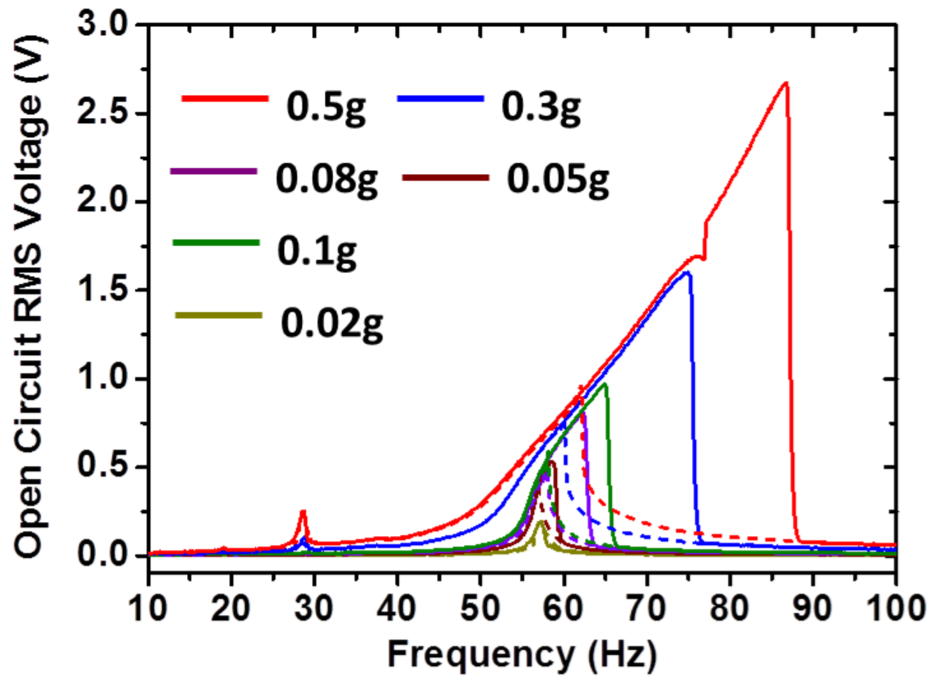
Advantages of FR4 (Flame Retardant 4):

- Standard PCB material
- Low Young's Modulus (21 GPa) – Useful for low frequency applications.
- Low cost !!

Meso-scale Prototype



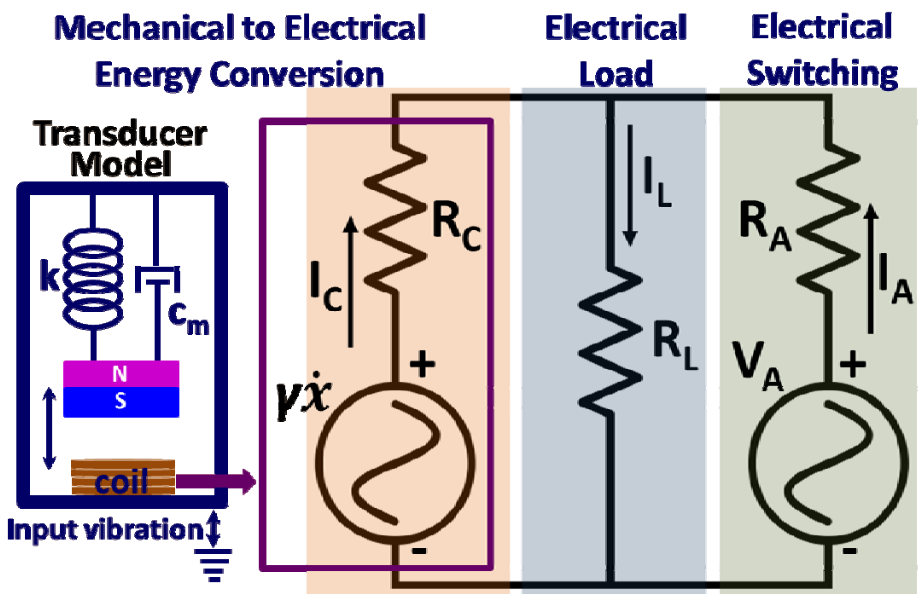
Volume = 2.65 cm^3
Mass = 3 gm



- **Bandwidth (BW) – 10 Hz @ 0.5g**
- **Maximum Power ~ 0.5 mW @ 0.5g**

D. Mallick et al, Smart Mater. Struct., 24, 015013 (2015).

Modelling of the Switching Scheme



$$V_A(t) = \begin{cases} V_{OA}\sin(2\pi f_A t) & for\ t_i \le t \le t_f \\ 0 & Otherwise \end{cases}$$

V_{OA} – Amplitude

f_A – frequency

t_i and t_f - starting and ending times of the switching period

The net current I_C through the coil: $I_C(\dot{x}, t) = I_L - I_A = \dfrac{\gamma\dot{x}}{R_C} - \dfrac{R_L}{R_C} \cdot \dfrac{V_A(t)R_C + \gamma\dot{x}R_A}{R_C R_A + R_A R_L + R_L R_C}$

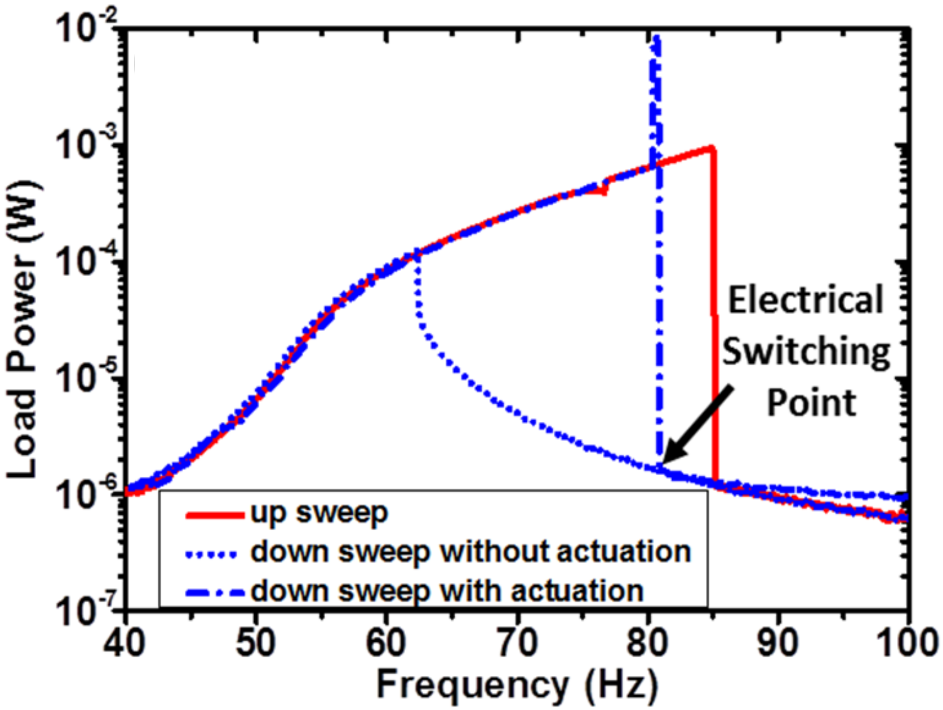
The coupled electromechanical equation of motion of the oscillator

$$m\ddot{x} + 2m\rho\omega_n\dot{x} + kx + k_n x^3 + \gamma I_C = -m\ddot{z}$$

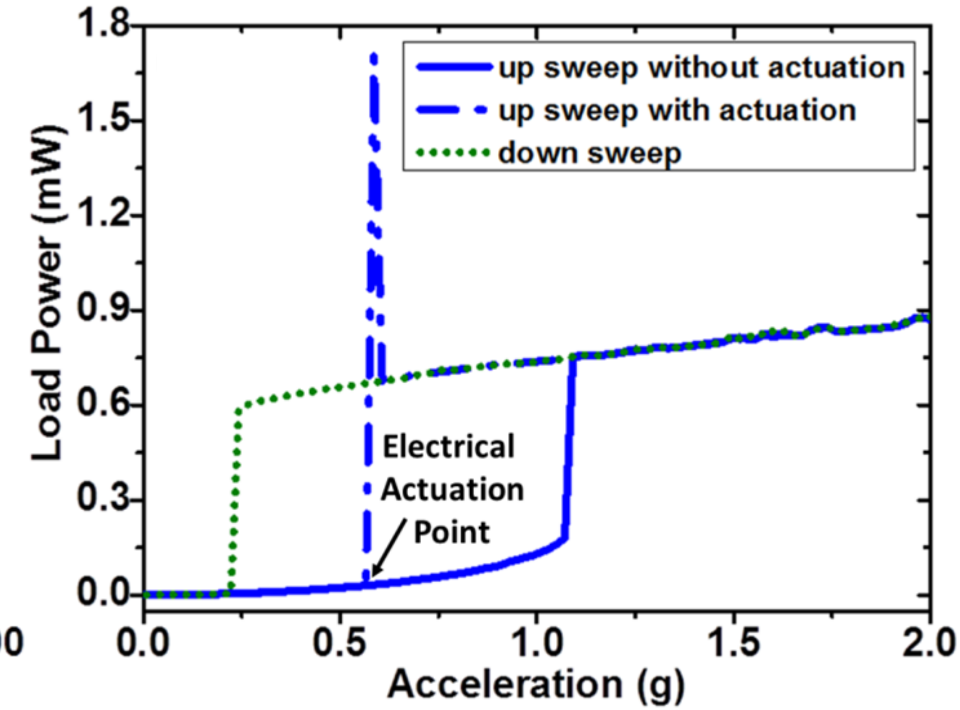
Surfing the High Energy Branch (II)

Altering the well established frequency/amplitude scan responses

Fixed Acceleration – 0.5g



Fixed Frequency – 70 Hz



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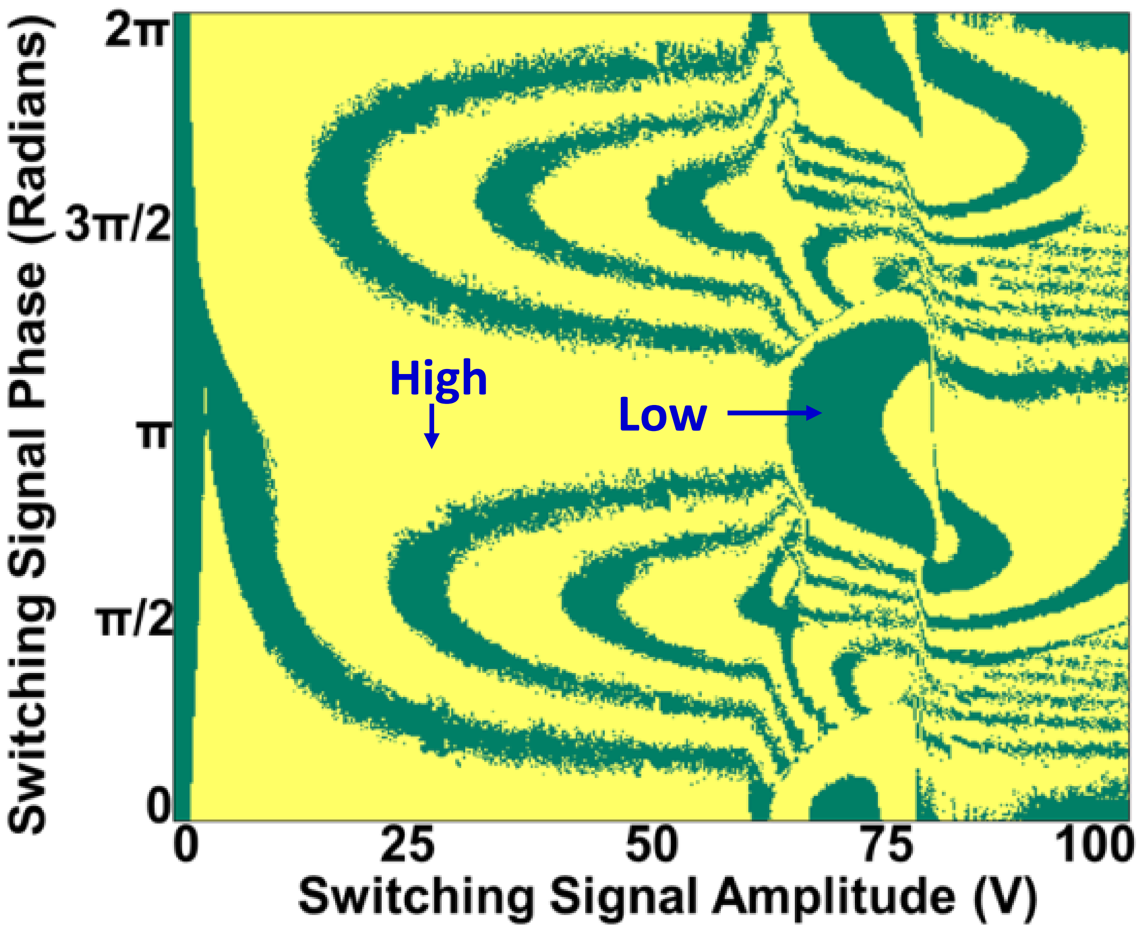

D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

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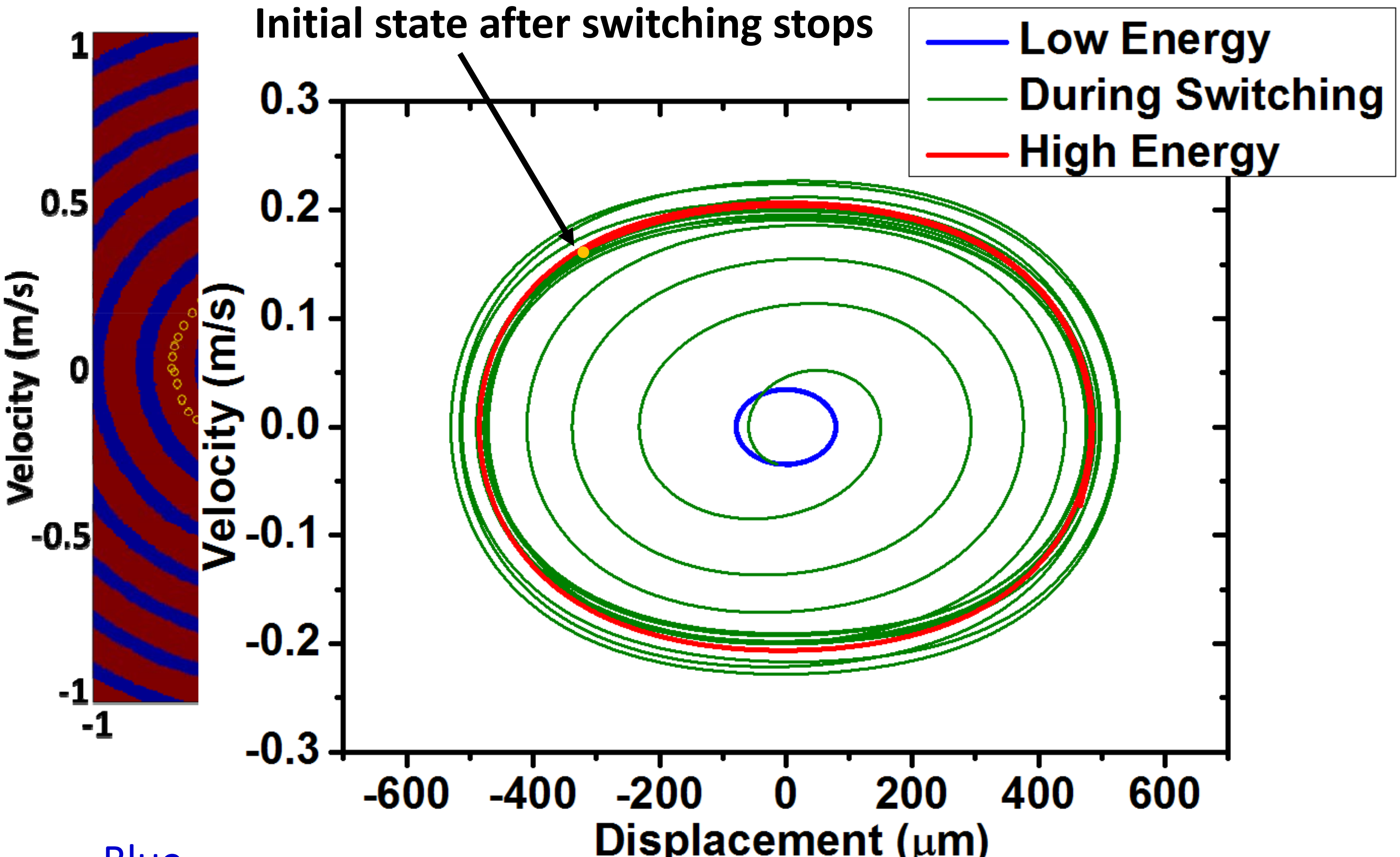

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Blue -

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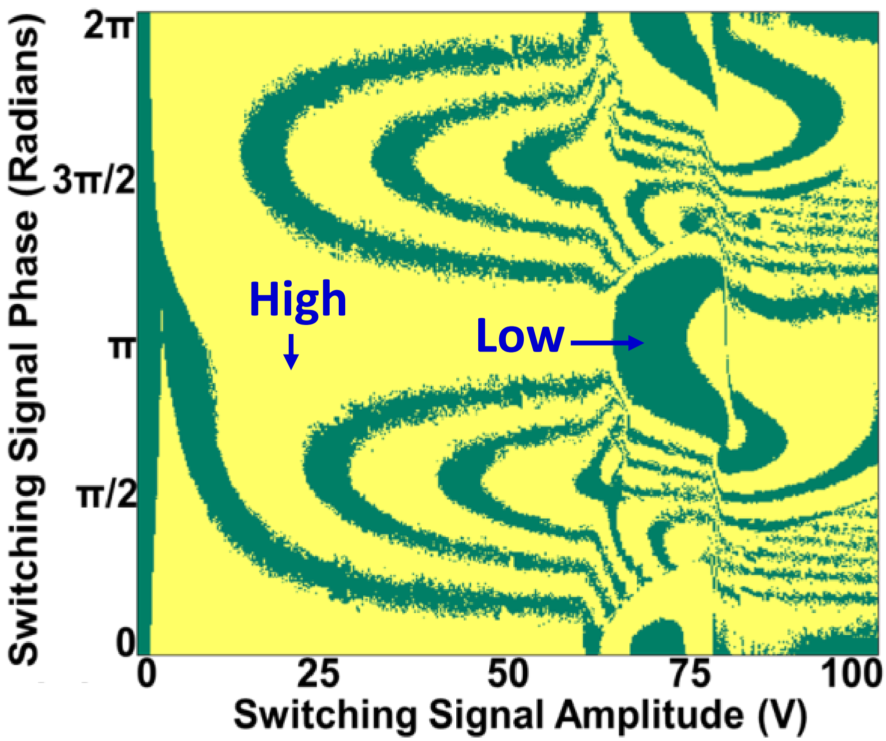
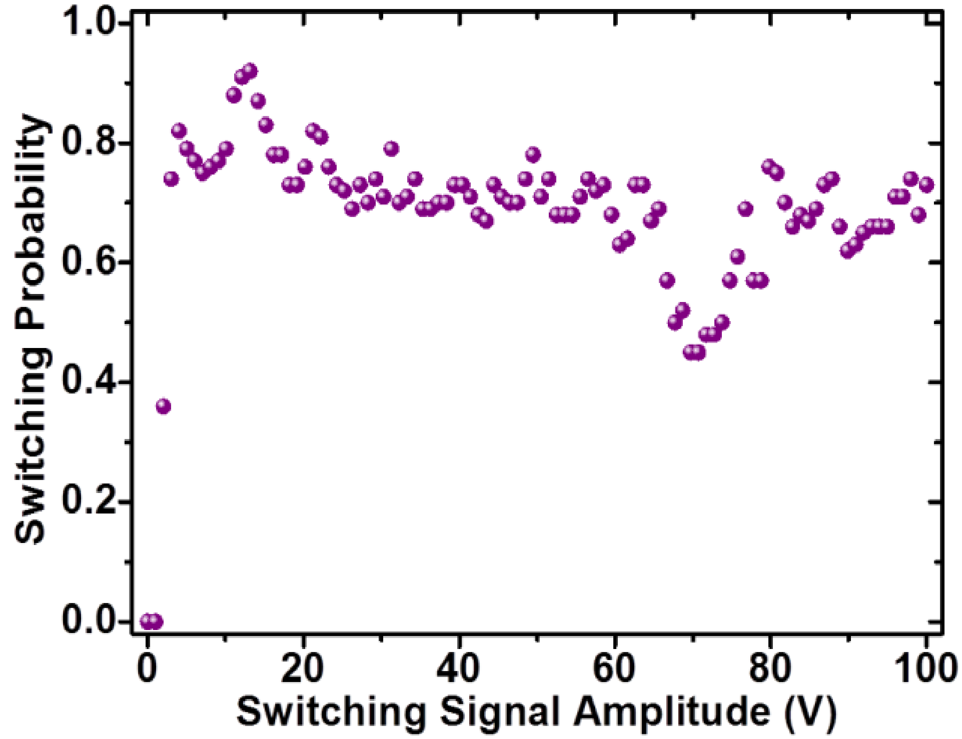
Probabilistic Study on Switching Mechanism

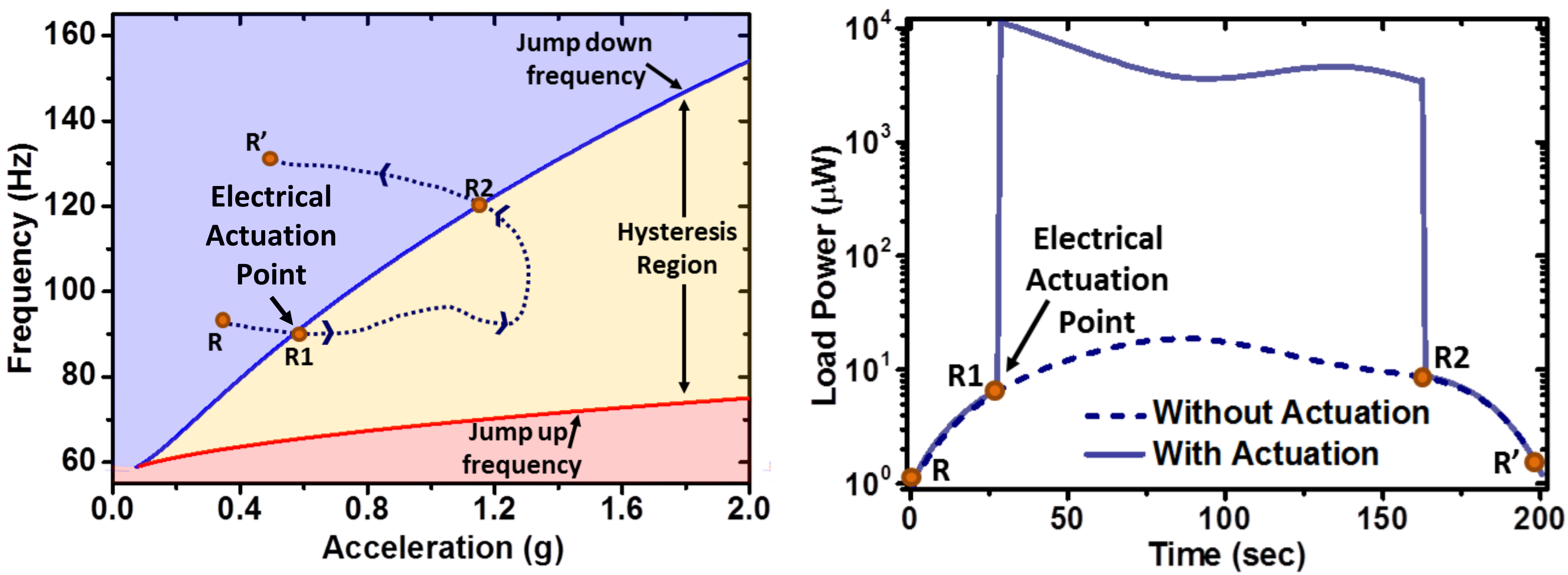




D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Surfing the High Energy Branch (III)

Response under randomly varying vibration

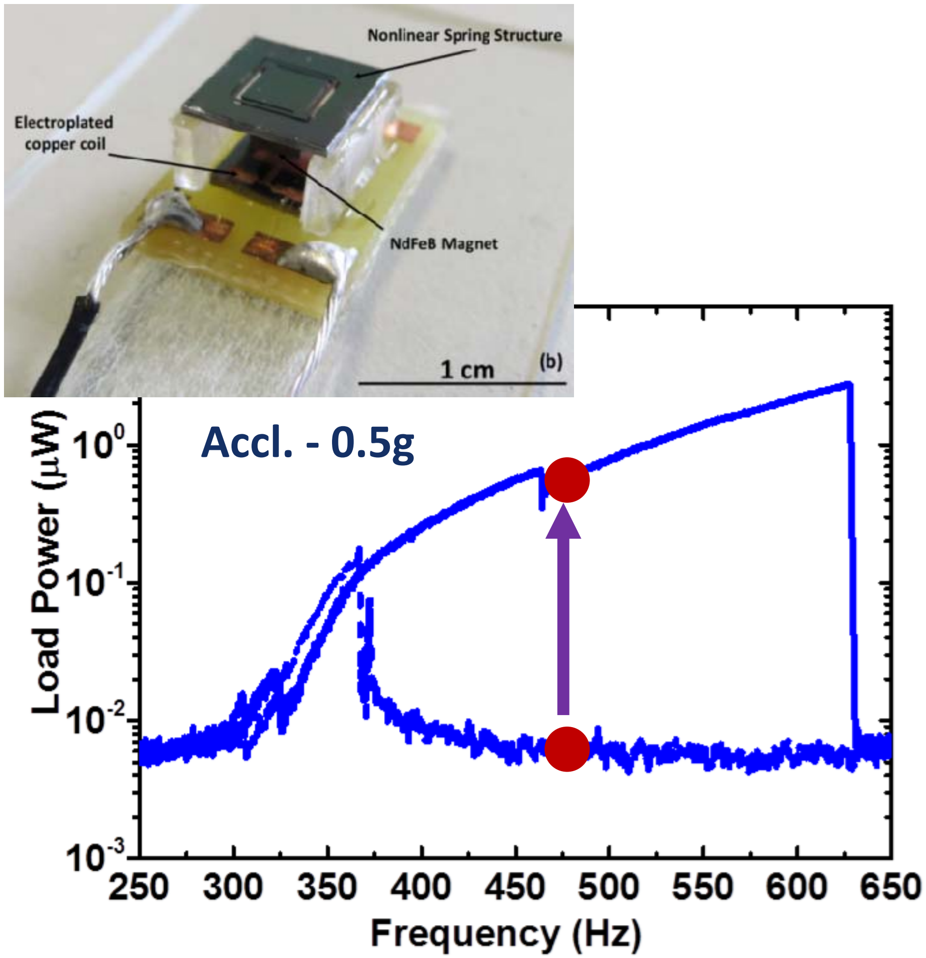


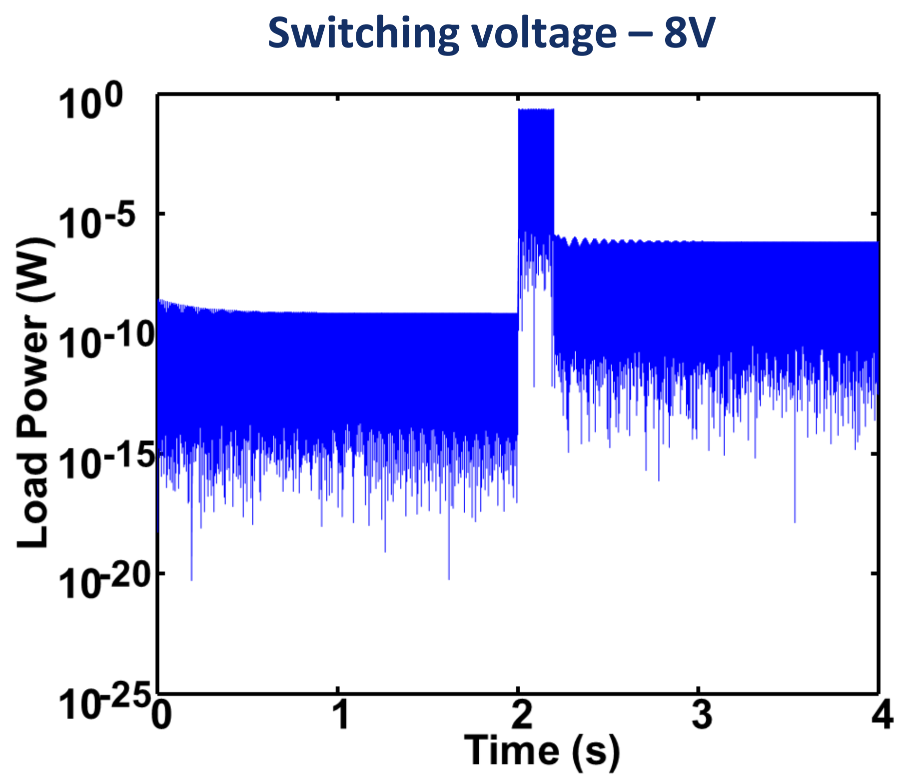
R → R' : frequency/amplitude varying input excitation

Increase in harvesting efficiency: 340 times

D. Mallick et al, Phys. Rev. Lett., 119:197701 (2016).

Electrical Switching in MEMS EM VEH

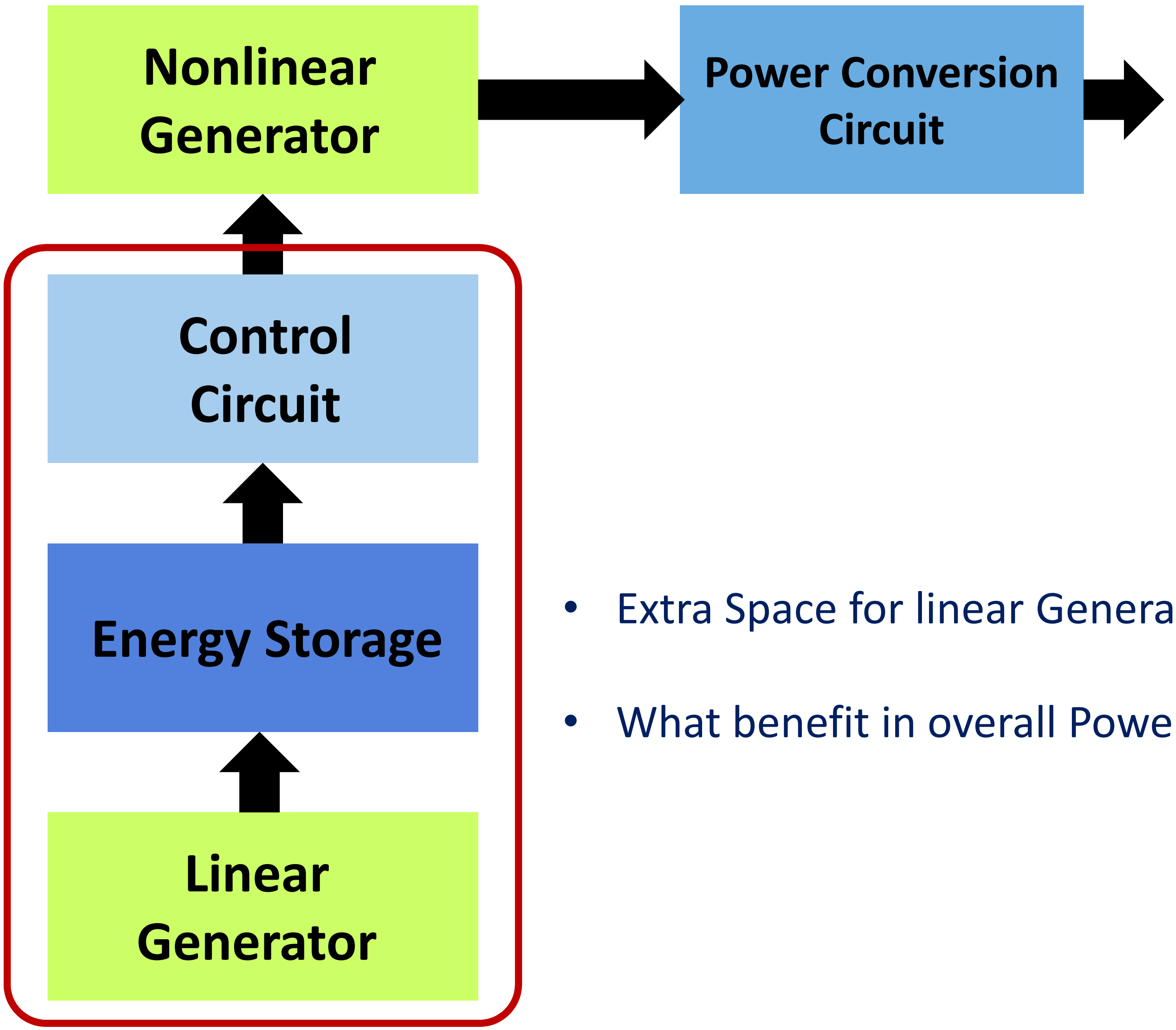




- Energy gap between High and Low energy branches is low
- Electromechanical coupling is very low as well
- Inefficient transfer of energy

Self-switching/Automatic Operation

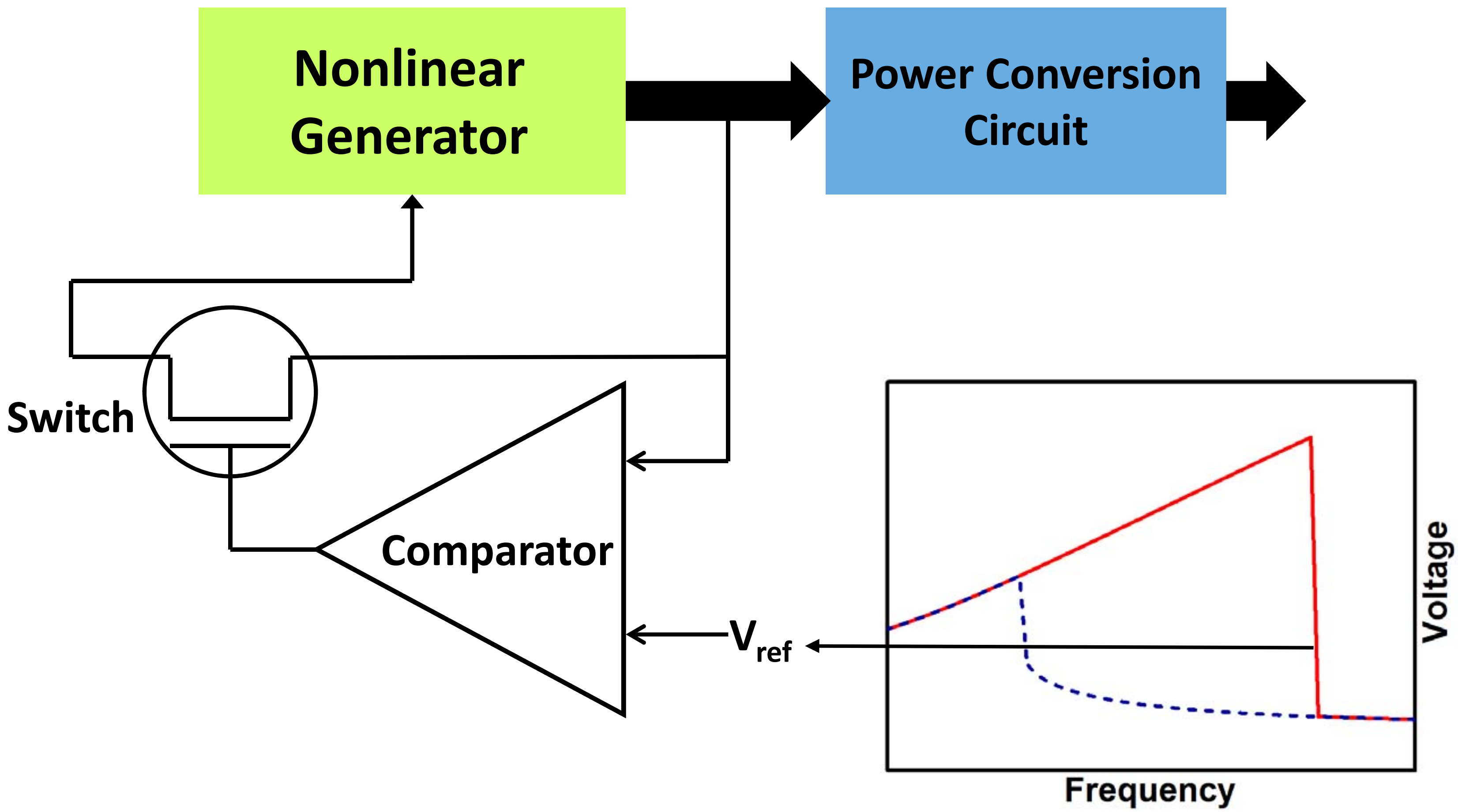
Proposed Scheme I



- Extra Space for linear Generator
- What benefit in overall Power Density?

Self-switching/Automatic Operation (II)

Proposed Scheme II



- Power loss even when there is no multi-stability