Energy Harvesters with High Electromagnetic Conversion Efficiency through Magnet and Coil Arrays

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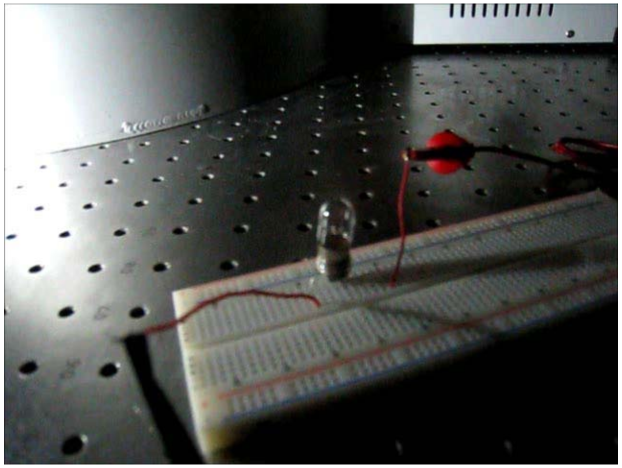
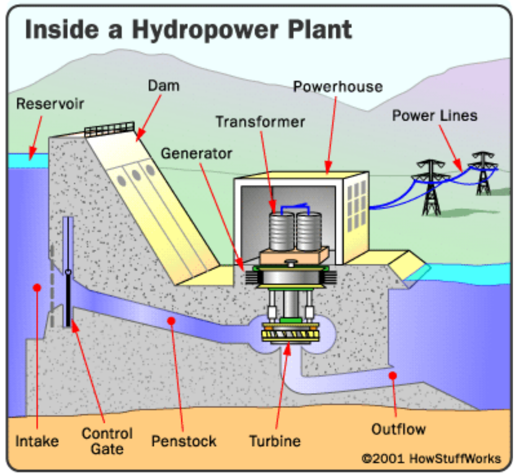
Outline



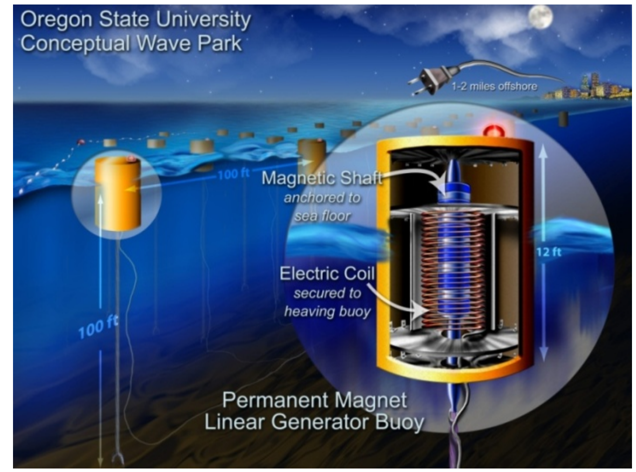
- Introduction
  - Electromagnetic energy harvesting
  - Power levels in recent harvesters
- Energy harvesters with magnet and coil arrays
  - Working principle
  - **Micro**fabricated energy harvester
    - MEMS fabrication, experimental testing setup and results
  - **Macro**scale energy harvester
    - Experimental results and video
- Summary

Renewable Energy Sources

Wind energy



Hydropower energy



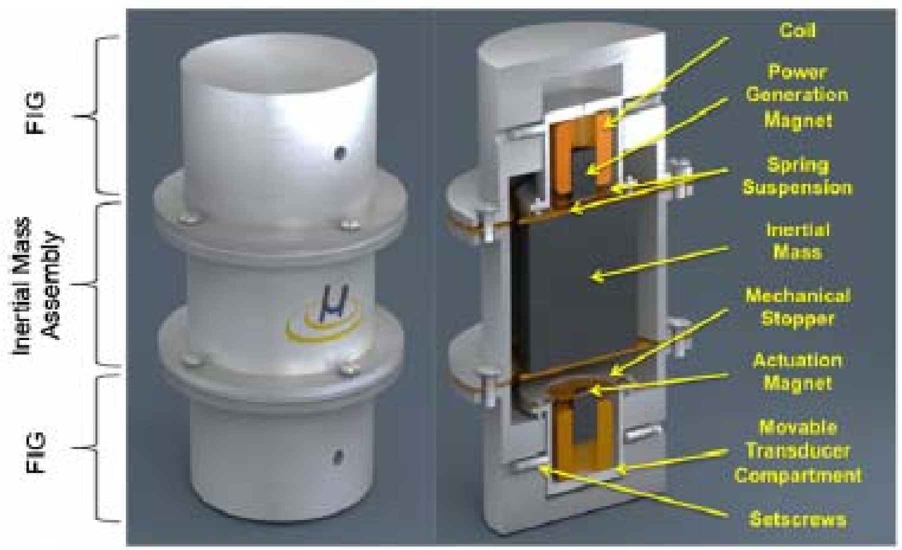
Ocean-wave energy

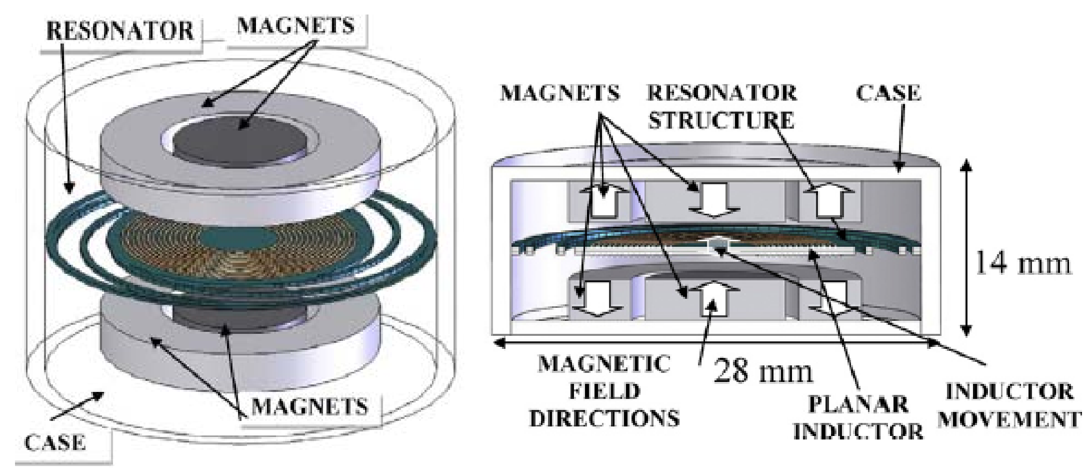
- From nature resources
  - Wind energy
  - Water energy
  - Wave energy
  - …

Kinetic energy ↓ **Electrical energy**

- Electromagnetic transduction
  - Faraday's law
  - Low working frequency
  - Low output impedance

Recent Electromagnetic Energy Harvesters





- Frequency-increased generator
  - Volume: 68cc
  - Vibration: 4mm at 2Hz (55mg)
  - Harvested power: 57µW

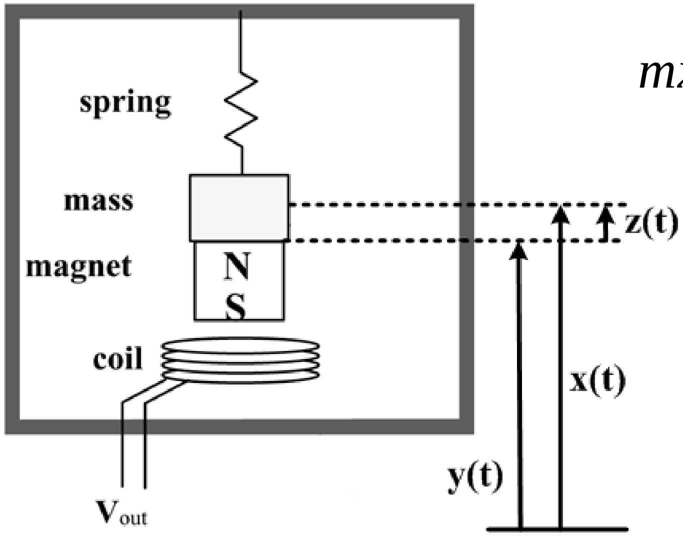
T.V. Galchev et al., JMM, 2011.

- Optimizing arrangement of magnets
  - Volume: 9.3cc
  - Vibration: 85µm at 102Hz (3.6g)
  - Harvested power: 290µW

E. Sardini et al., Sensors and Actuators A, 2011.

Power ?

Model of Vibration-Driven Power Generator

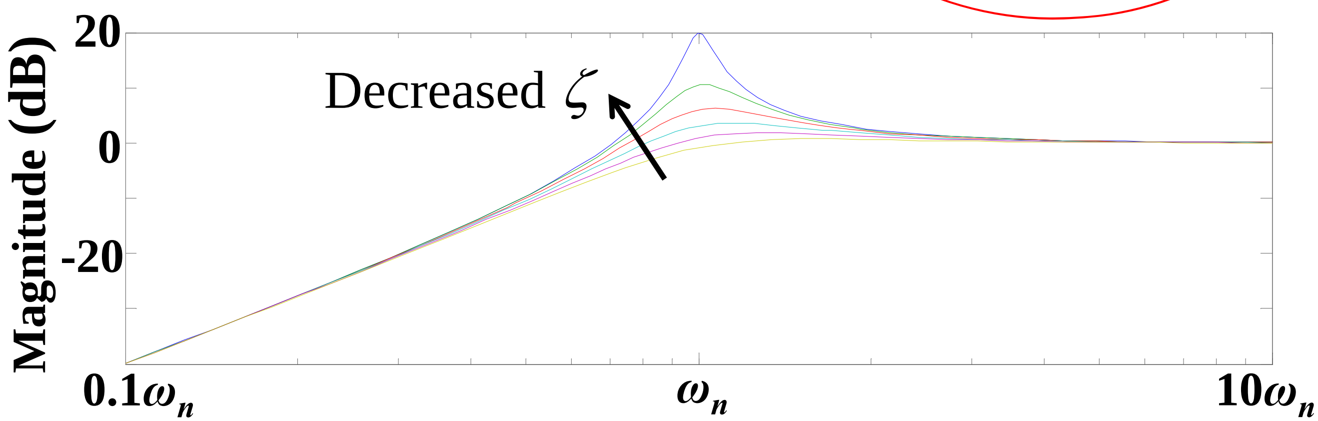


Equation of motion

$$mx(t)'' + dz(t)' + k_s z(t) = 0$$

$$z(t) = x(t) - y(t)$$

$$\Rightarrow \quad Z_0 = Y_0 \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}$$



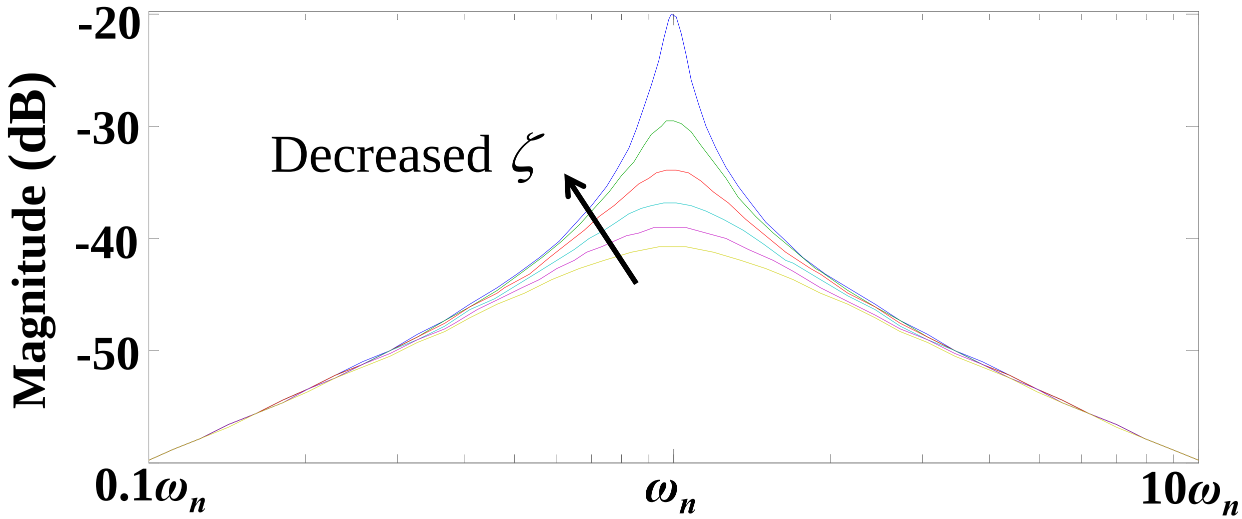
Faraday's law

$$\varepsilon = N\frac{d\psi}{dt} = NS\frac{dB}{dz}\frac{dz}{dt} = NS\frac{dB}{dz}\omega Z_0 = NS\omega Y_0 \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}\frac{dB}{dz} = NSA_0 \frac{\frac{\omega}{\omega_n^{\,2}}}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}\frac{dB}{dz}$$

$(A_0 = \omega^2 Y_0)$

Increasing Power Output

$$\varepsilon = NSA_0 \frac{\dfrac{\omega}{\omega_n^{\,2}}}{\sqrt{\left(1-\left(\dfrac{\omega}{\omega_n}\right)^2\right)^2+\left(2\zeta\dfrac{\omega}{\omega_n}\right)^2}}\frac{dB}{dz}$$

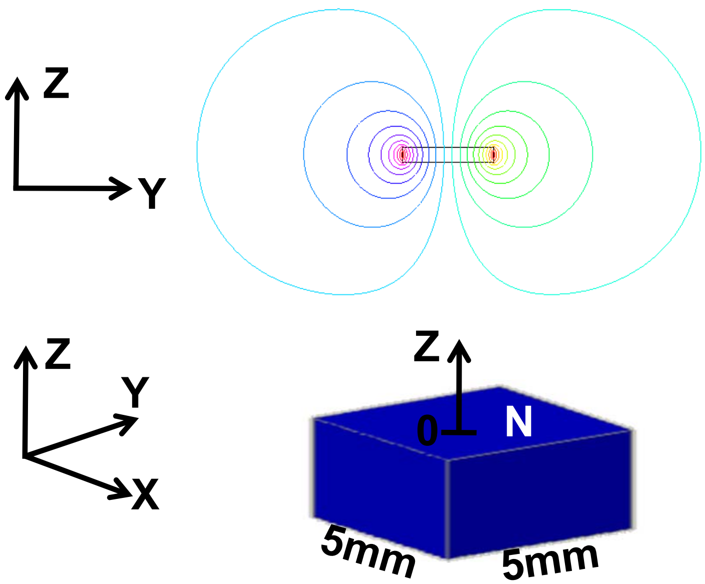


At resonant frequency ($\omega=\omega_n$) $\varepsilon = NS\omega_n Y_0 \dfrac{1}{2\zeta}\dfrac{dB}{dz}$

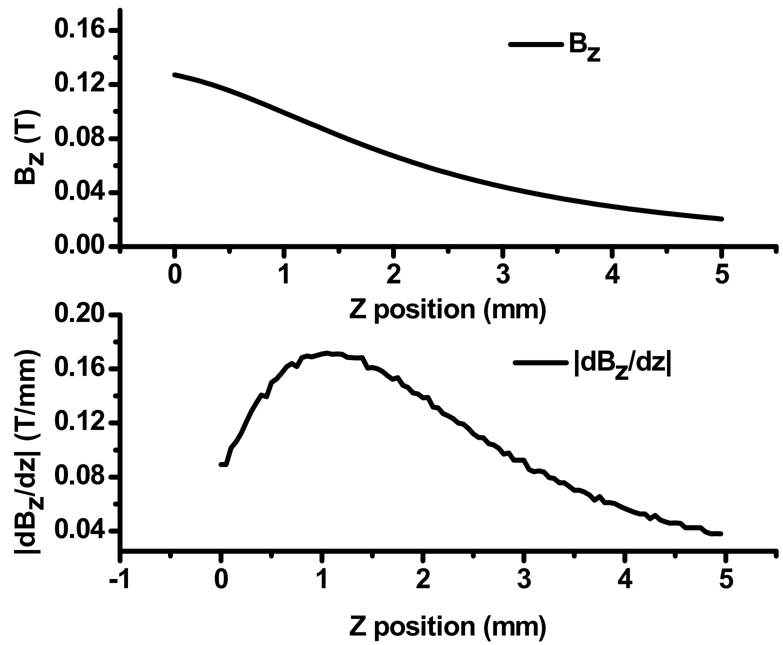
$$\frac{dB}{dz}\,?$$

- To increase power output,
  - increase N and S ⟶ larger volume and weight
  - increase ω_n and Y_0 ⟶ more vibration energy

Magnetic Flux Change – One Magnet



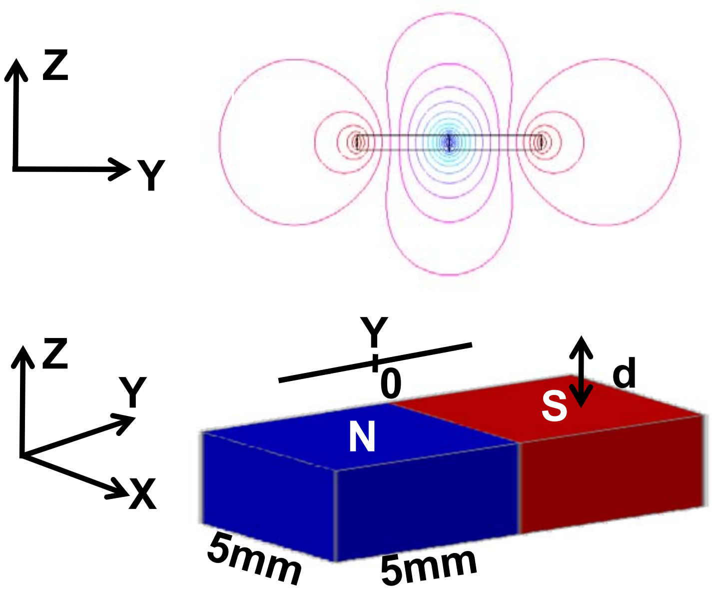
Magnetic field lines



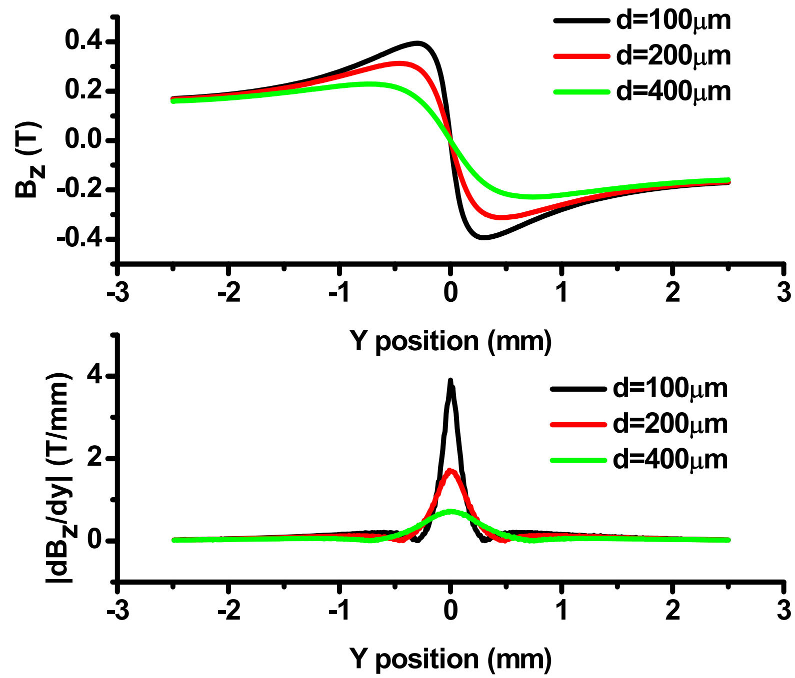
Magnetic flux density (B_z) and its gradient (dB_z/dz)

- When magnetic field is provided by a single magnet,
  - magnetic flux change is caused by a distance change.

Magnetic Flux Change – Two Magnets



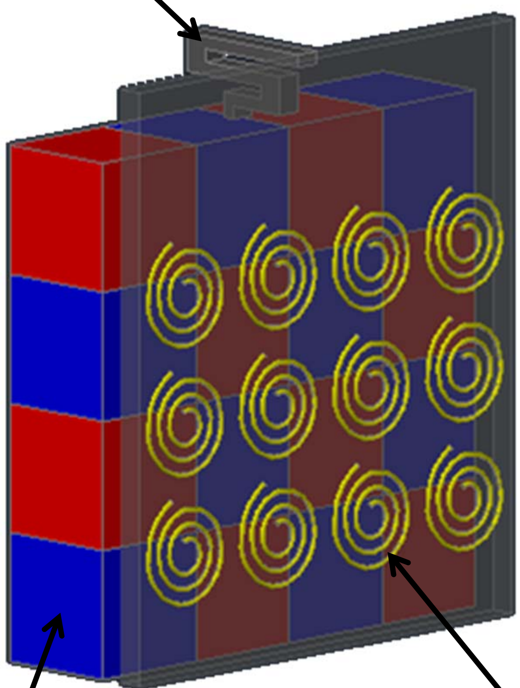
Magnetic field lines



Magnetic flux density (B_z) and its gradient (dB_z/dy)

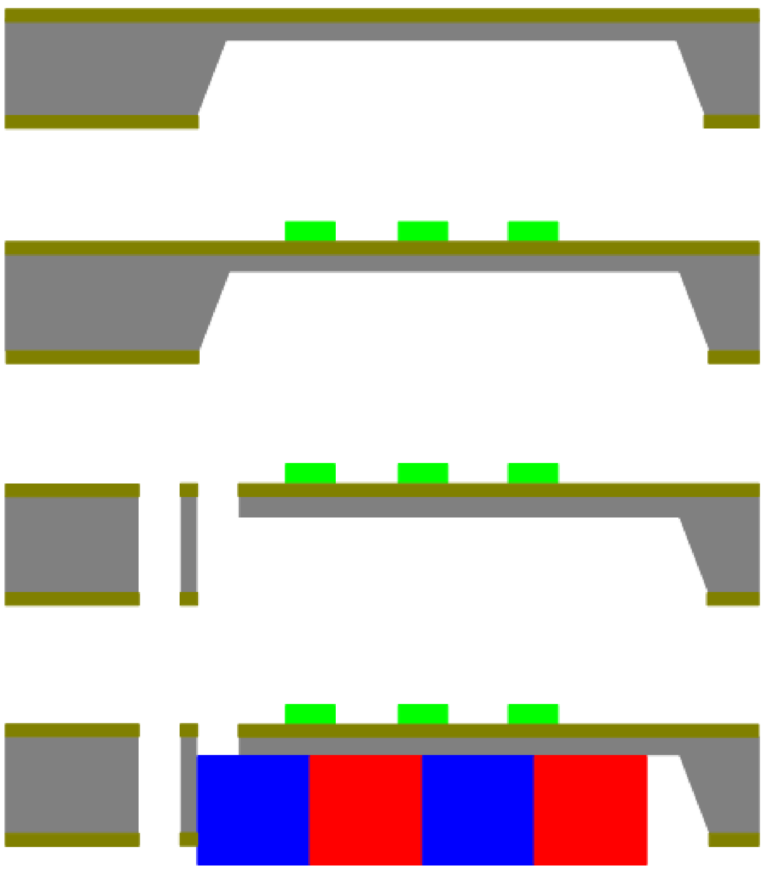
- When magnetic field is provided by two magnets through alternating north- and south-orientation on a planar surface,
  - magnetic flux changes in the direction parallel to the planar surface
  - peaking at the boundary between two magnets
  - increasing as the distance (d) from the magnet surface is decreased

Energy Harvester with Magnet and Coil Arrays



- Magnet array with alternating north- and south-orientation on a planar surface
- Coil array over the boundaries between the magnets
- Vibration direction parallel to the planar surface
- Gap between magnet array and coil array as close as possible

Fabrication Steps Microfabricated Energy Harvester



(a) KOH etching

(b) Electroplating copper

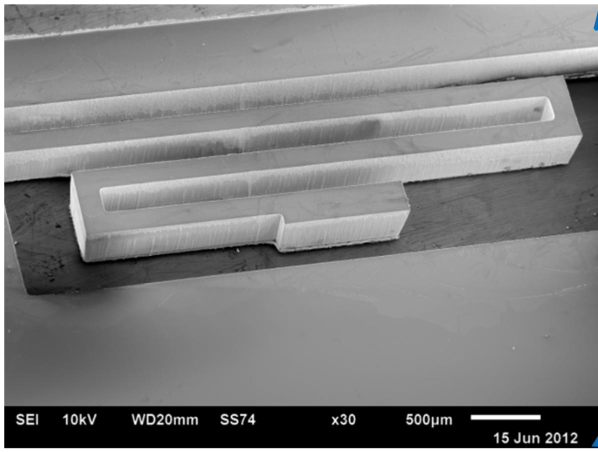
(c) Si etching by DRIE

(d) Assembling magnets

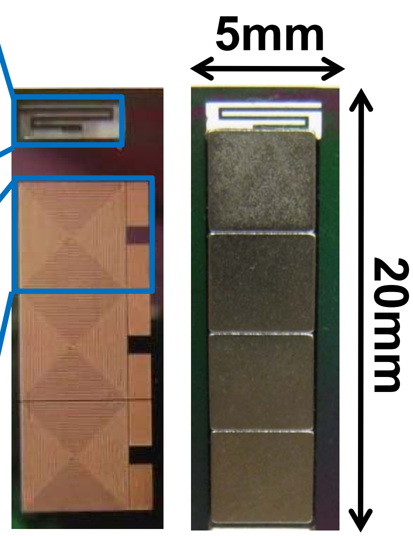
- Narrow gap between the magnet array and coil array
- Microdiaphragm-based front-to-backside alignment technique

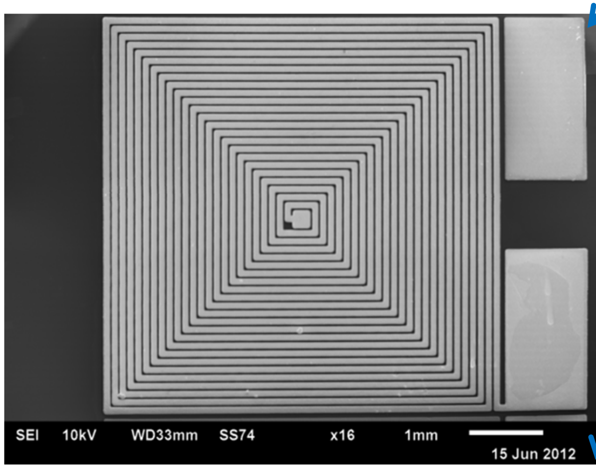
Microfabricated Electromagnetic Energy Harvester

Top-view and bottom-view



200µm wide two-fold spring



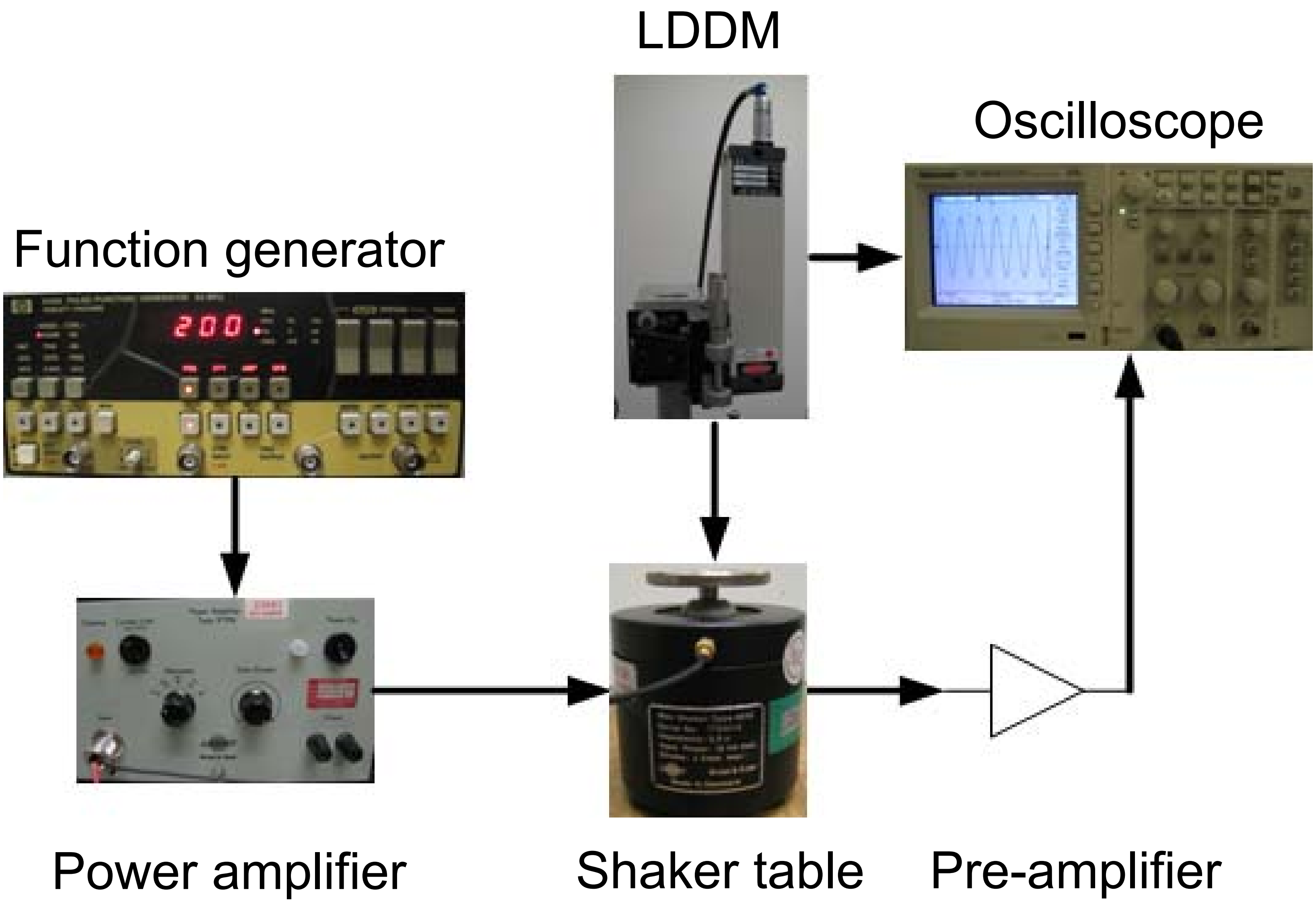


20-turn spiral coil

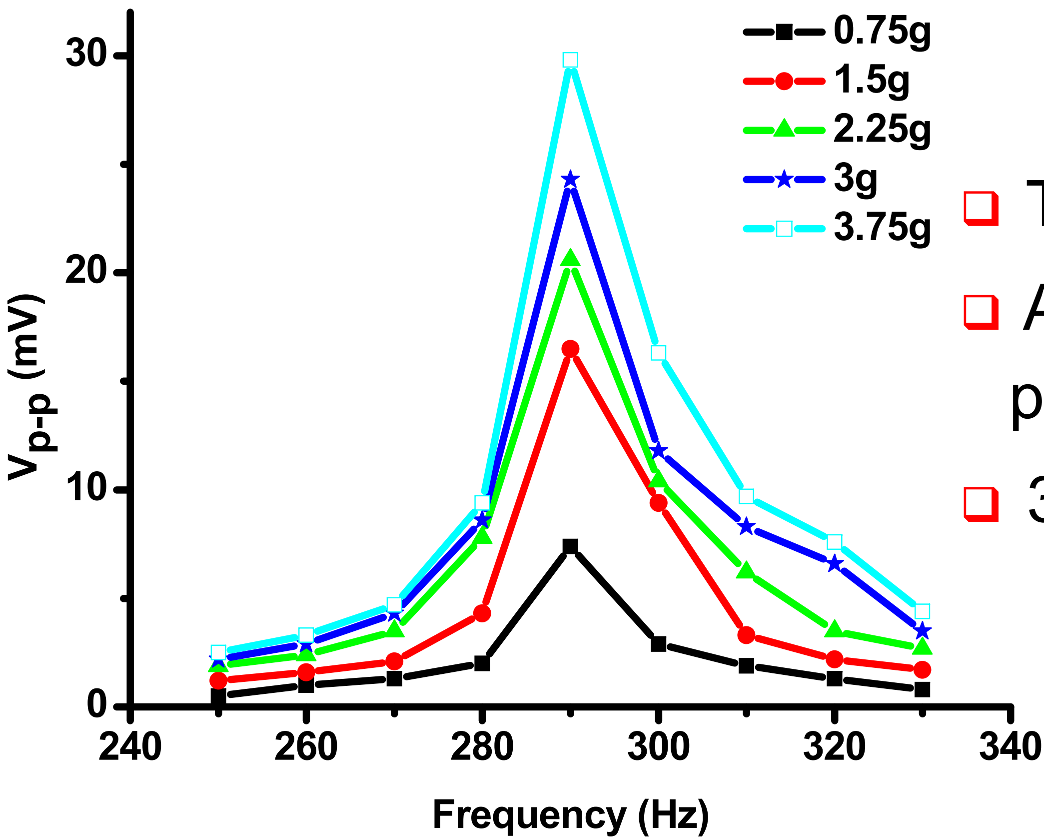
Detailed parameters

Total volume (mm^3)	20×5×0.9 (0.09cc)
Weight (gram)	0.5
Magnet size (mm^3)	4.8×4.8×0.8
Coil thickness (µm)	22
Coil turns	20
Coil resistance (Ω)	3.6
Coil number	3

Testing Setup

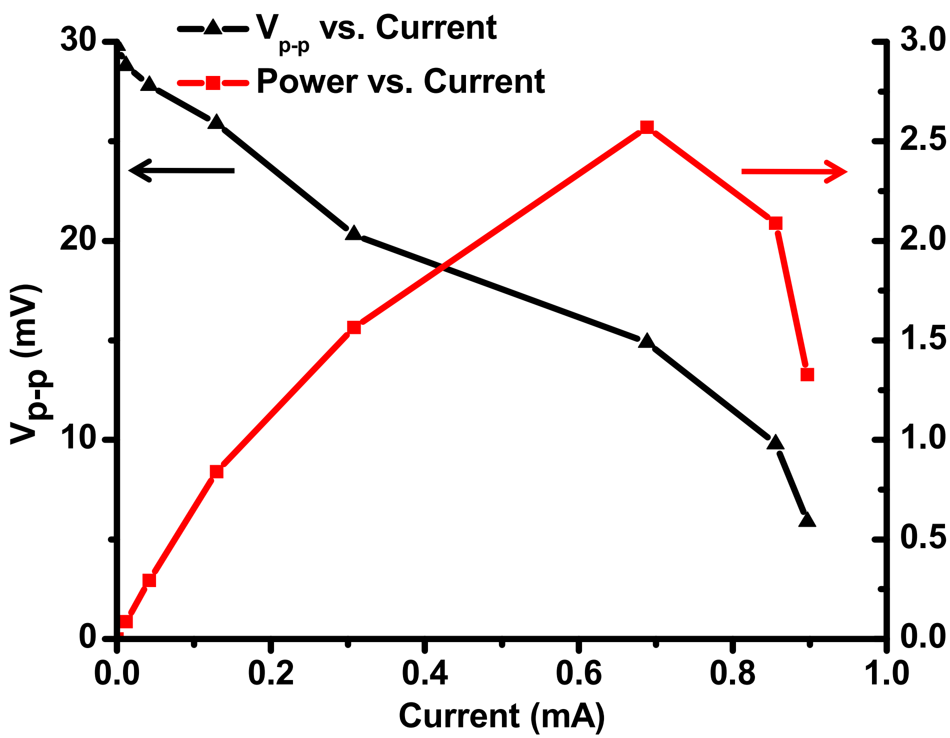


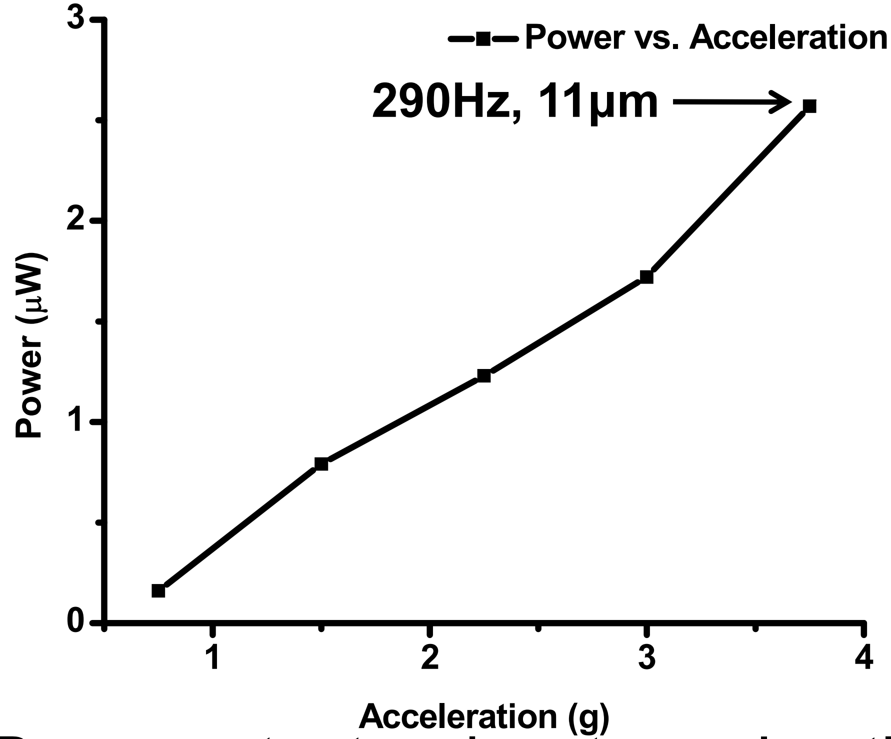
Measured Electromotive Force (EMF) vs Vibration Frequency



- Three coils are connected in series
- At a fixed acceleration, the EMFs peak at the resonant frequency
- 30mV_{p-p} from 3.75g at 290Hz

Power Output Delivered to Loads





- Output voltage and power across a load
  - for different resistances
  - with the largest power delivered to a matched load
- Power output vs input acceleration
  - into 10.8Ω load
  - at the resonant frequency
  - 2.6μW is delivered from 3.75g acceleration at 290Hz (vibration amplitude = 11μm)

Summary of Microfabricated Energy Harvester

Total volume (mm^3)	20×5×0.9 (0.09cc)
Weight (gram)	0.5
Resonant frequency (Hz)	290
Vibration amplitude (μm)	11
Input acceleration (g)	3.75
Open circuit voltage (mV_{p-p})	30
Load resistance (Ω)	10.8
Power output (μW)	2.6

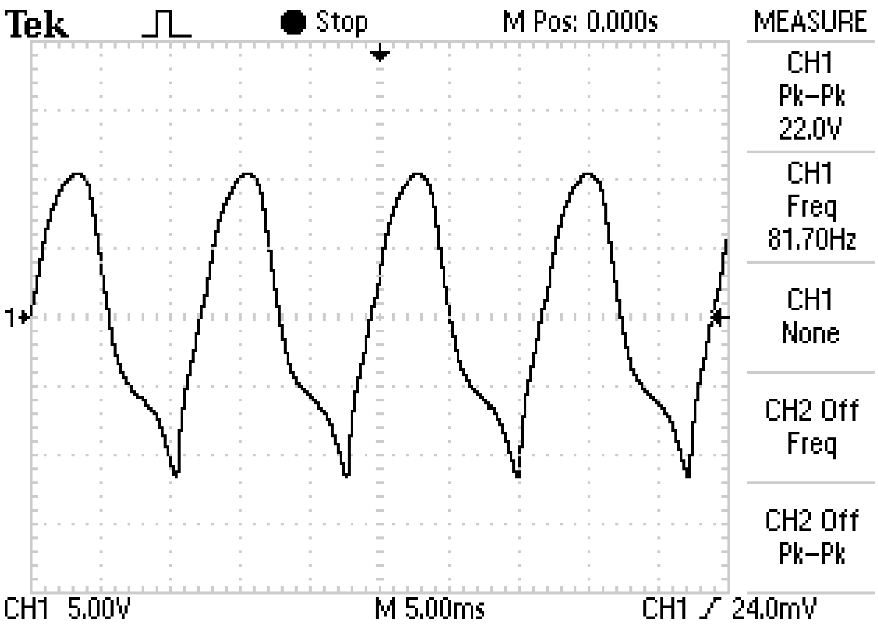
- Resonant frequency can be adjusted by design of silicon cantilever
- Coil resistance can be reduced by electroplating thick copper
- Number of array can be increased easily for mass production

Macroscale Energy Harvester

Detailed parameters

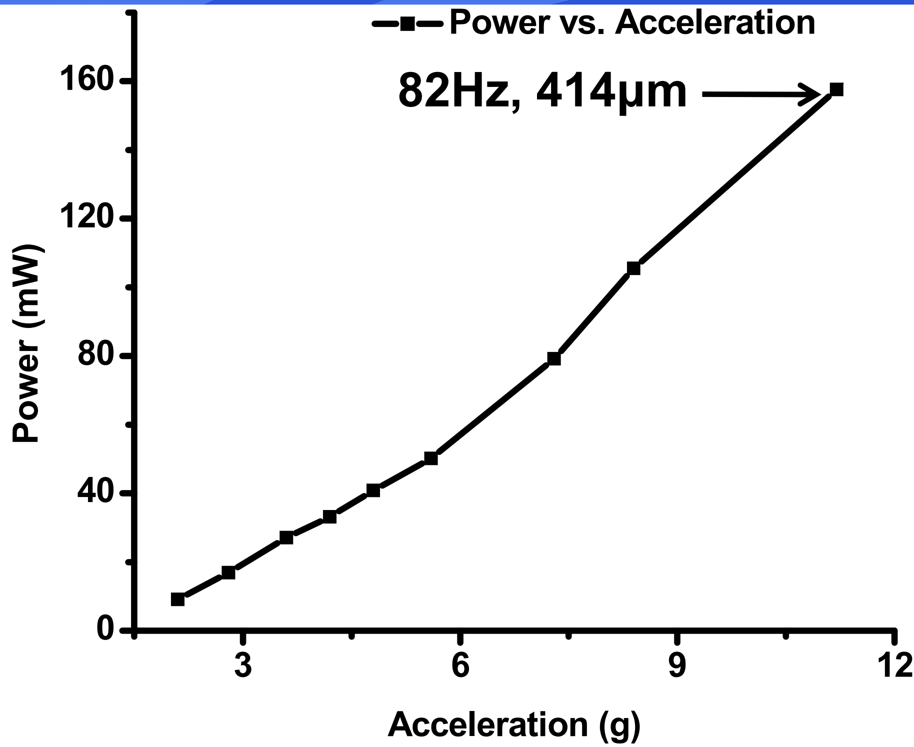
Total volume (mm^3)	51×51×10 (26cc)
Weight (gram)	90
Magnet size (mm^3)	12.7×12.7×3.2
Coil turns	200
Coil resistance (Ω)	8
Coil number	12

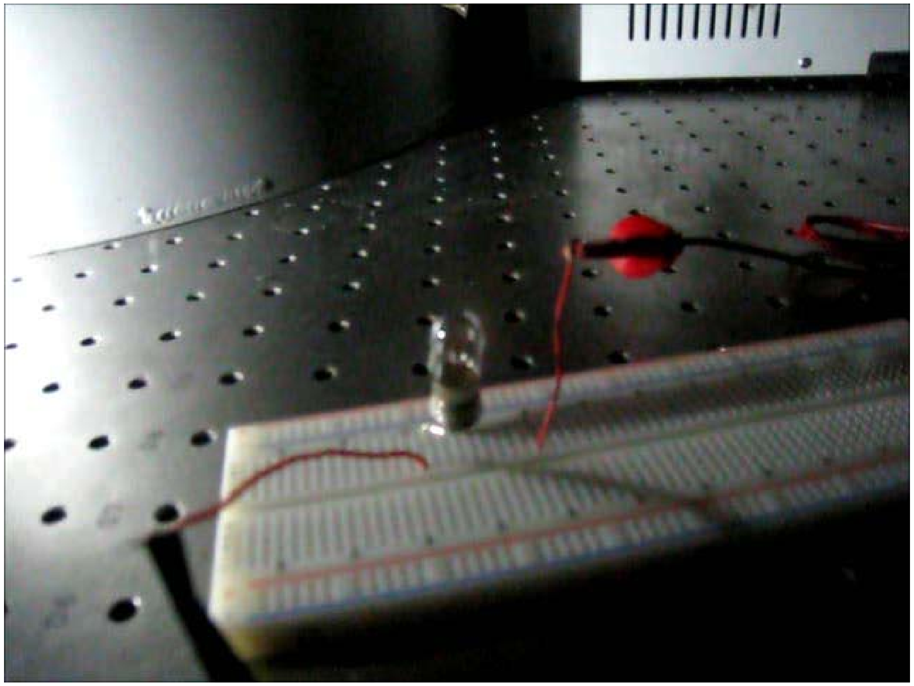
Measured EMF



- Scaled up to 16 magnets and 12 coils
  - 12 coils are connected in series
  - $V_{p\text{-}p}$=22V at a resonant frequency of 82Hz with vibration amplitude of 414μm

Power Output Delivered to Load





- Power output vs. input acceleration
  - into 96Ω load
  - 158mW is delivered from 11.2g acceleration at 82Hz (vibration amplitude of 414μm)
- Demo of the energy harvester
  - 120mW incandescent light bulb
  - Directly connected
  - Close to the bulb's full capacity

Summary

- A new electromagnetic-transduction idea to increase the mechanical-to-electrical conversion efficiency
  - array of magnets is used to provide a rapidly changing magnetic field
- The microfabricated energy harvester, occupying a volume of 0.09cc weighing 0.5 gram, produces 2.6μW at 290Hz (vibration amplitude of 11μm)
- The macroscale version, that is scaled up to 26cc weighing 90 gram, generates 158mW at 82Hz (vibration amplitude of 414μm), and lights an incandescent light bulb