Energy Harvesting
An EPSRC Funded Network
EPSRC

Vibration Energy Harvesting using Multi-Frequency and Nonlinear Piezoelectric Converters

Vittorio Ferrari

Department of Information Engineering
University of Brescia - ITALY

- Acknowledgments and credits to:
  - Davide Alghisi
  - Marco Baù
  - Simone Dalola
  - Marco Demori
  - Marco Ferrari
  - Michele Guizzetti
  - Daniele Marioli
  - Emanuele Tonoli

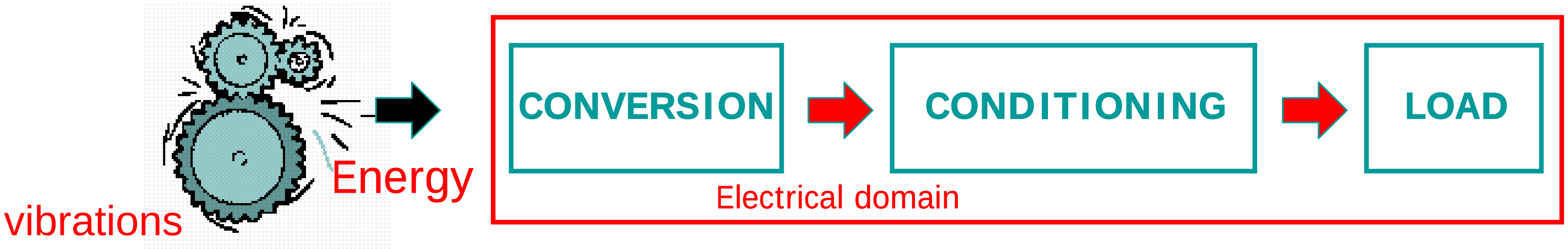
Contents

- Introduction
- Multi-frequency piezoelectric harvester arrays
- Nonlinear piezoelectric harvesters
- Conclusions

Contents

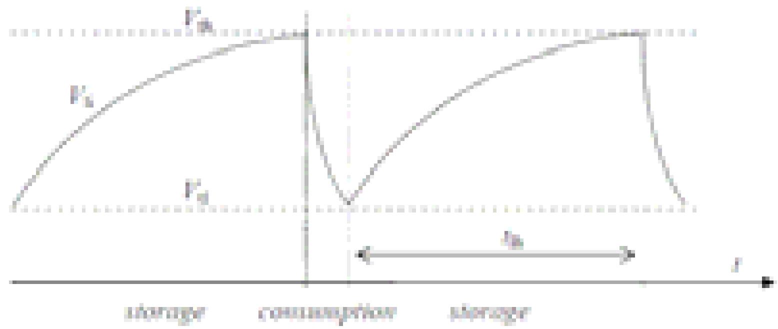
- Introduction
- Multi-frequency piezoelectric harvester arrays
- Nonlinear piezoelectric harvesters
- Conclusions

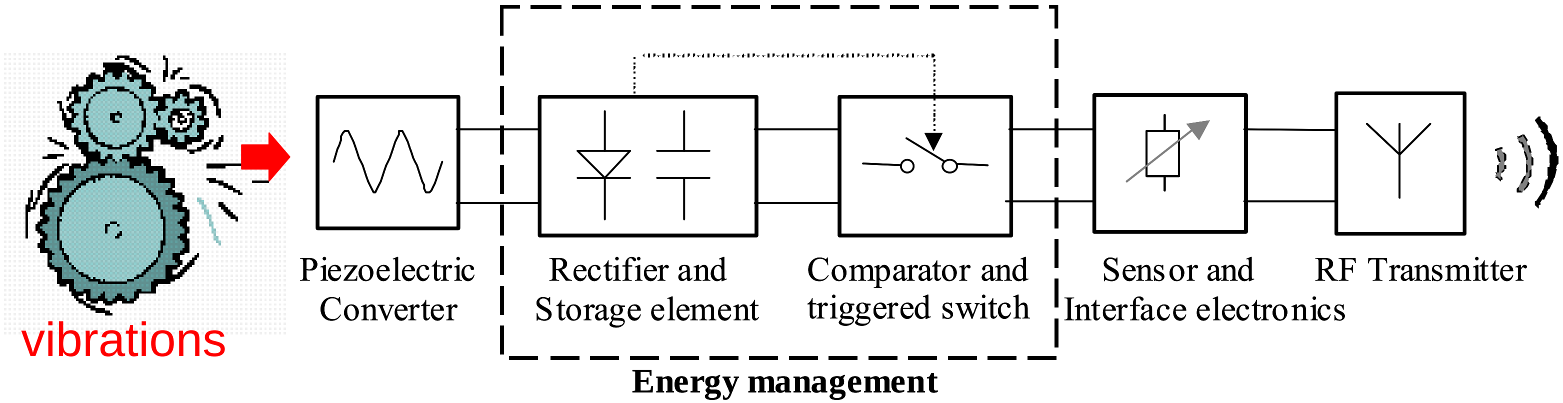
Vibration Energy Harvesting



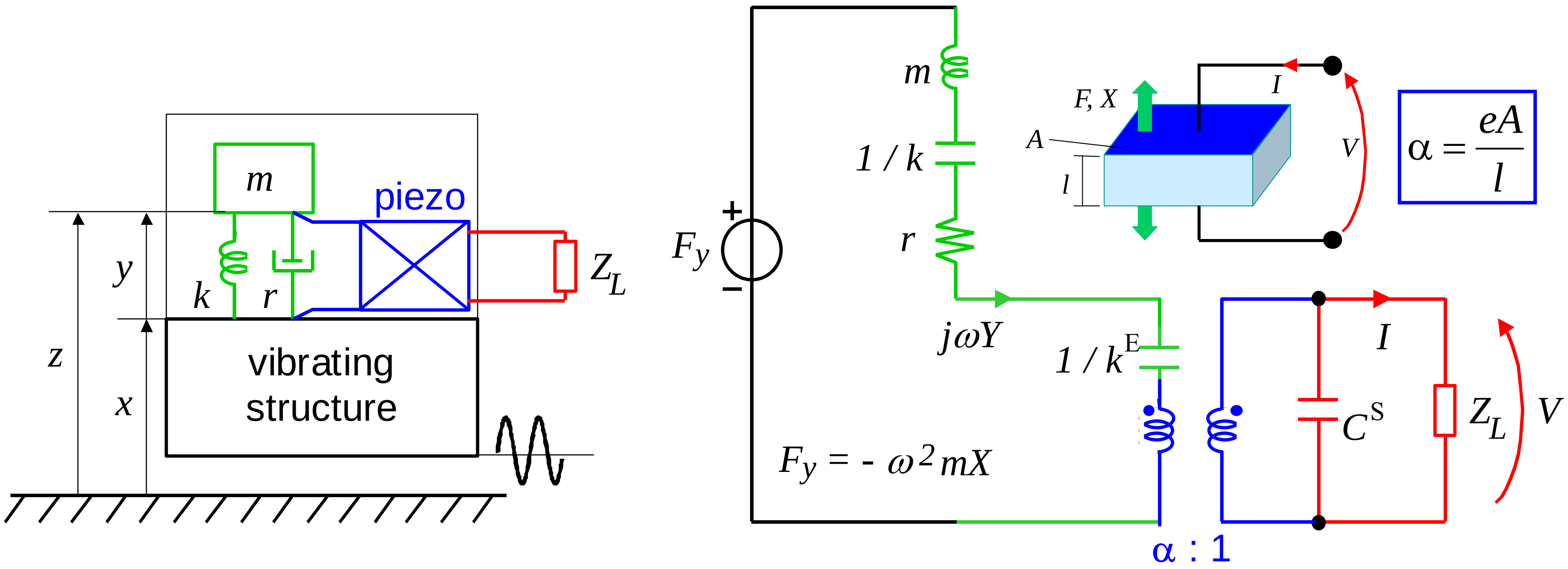
- The load can be sensors with wireless communication:
  → **Autonomous Sensors**

- If available power is insufficient for continuous operation
  → **Intermittent operation**





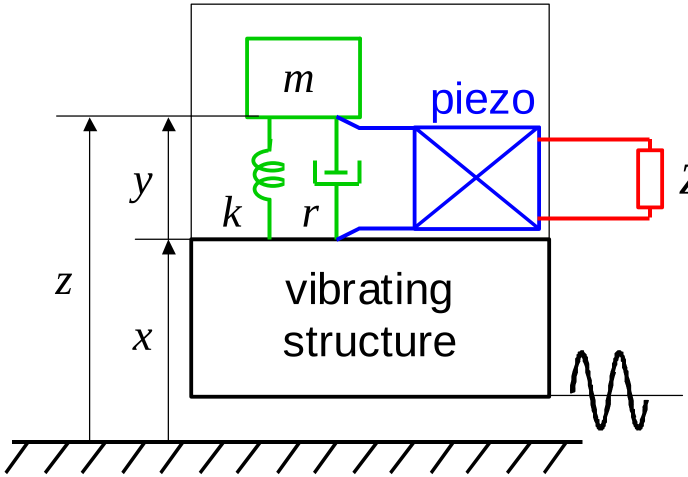
Piezoelectric Power Conversion

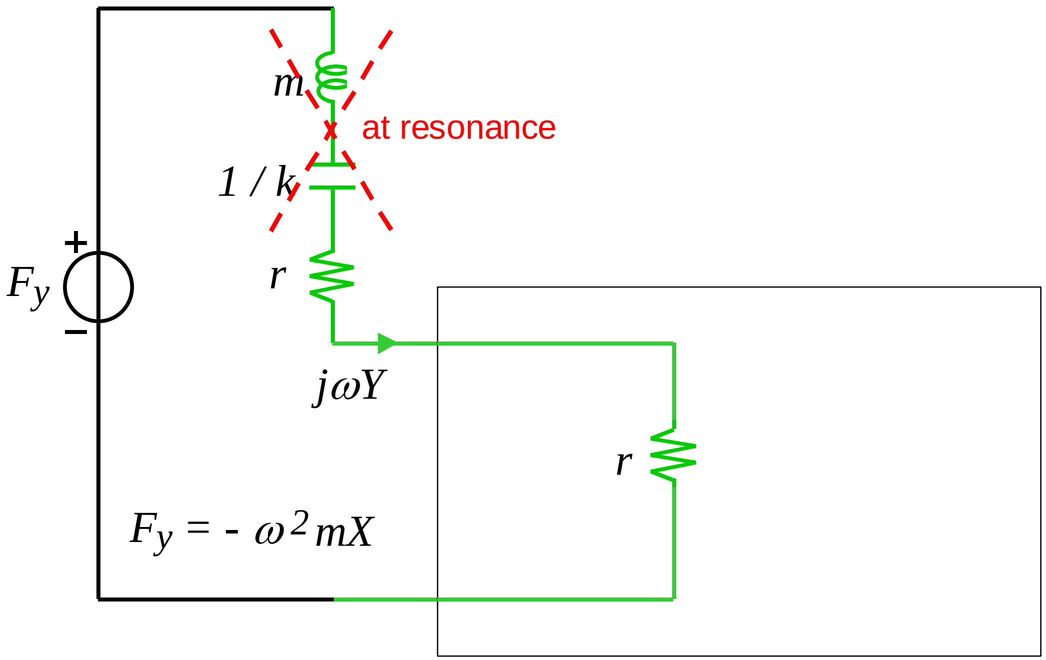


- A maximum exists to the power that can be extracted by an ideal converter, irrespective of the conversion principle
- This power limit occurs at resonance and for a converter with a purely resistive mechanical impedance adapted to *r*:

$$P_{\lim} = \frac{m^2 \ddot{X}^2}{8r} = \frac{m^2 a_x^2}{8r}$$

Piezoelectric Power Conversion





- A maximum exists to the power that can be extracted by an ideal converter, irrespective of the conversion principle
- This power limit occurs at resonance and for a converter with a purely resistive mechanical impedance adapted to r:

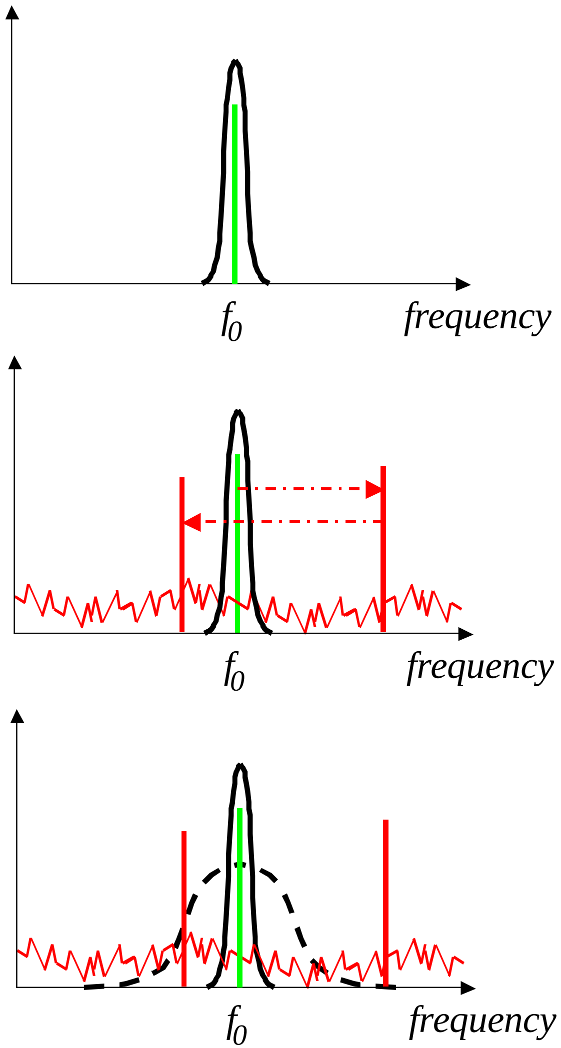
$$P_{\lim} = \frac{m^2 \ddot{X}^2}{8r} = \frac{m^2 a_x^2}{8r}$$

- Same results as in:

C.B. Williams, R.B. Yates,, *Sens. Actuat. A* **52**, 8-11 (1996).

Limitations with Resonant Converters

- Best harvesting effectiveness is when the converter operates at mechanical resonance
- This is problematic to guarantee with frequency-varying vibrations and is considerably sub-optimal for broadband and random vibrations
- Lowering the converter quality factor increases the bandwidth, but worsens the peak response



Broadband Approaches

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. 21 (2010) 022001 (29pp) doi:10.1088/0957-0233/21/2/022001

TOPICAL REVIEW

Strategies for increasing the operating frequency range of vibration energy harvesters: a review

Dibin Zhu, Michael J Tudor and Stephen P Beeby

School of Electronics and Computer Science, University of Southampton, SO17 1BJ, UK

Toward Broadband Vibration-based Energy Harvesting

LIHUA TANG, YAOWEN YANG* AND CHEE KIONG SOH

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

JOURNAL OF INTELLIGENT MATERIAL SYSTEMS AND STRUCTURES, Vol. 21—December 2010

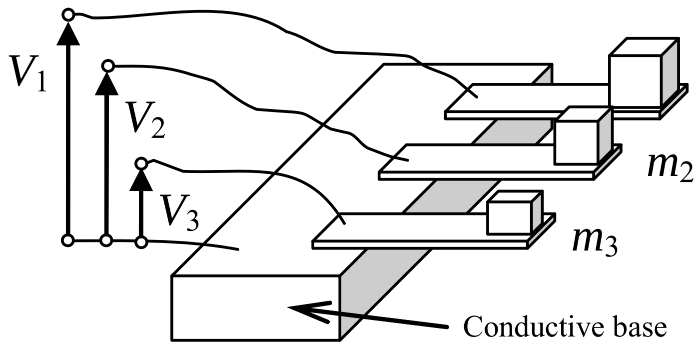
- Resonance tuning
- Multi-modal/multi-frequency harvesters
- Frequency-up conversion
- Nonlinear

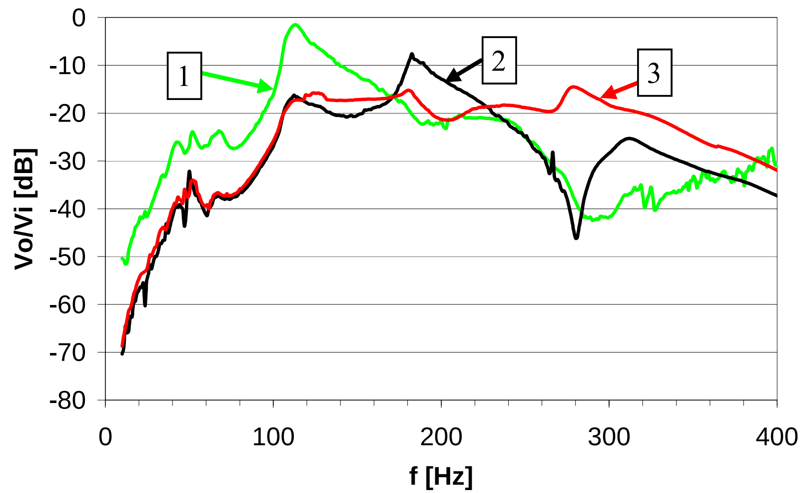
Contents

- Introduction
- Multi-frequency piezoelectric harvester arrays
- Nonlinear piezoelectric harvesters
- Conclusions

Multi-Frequency Converter Array

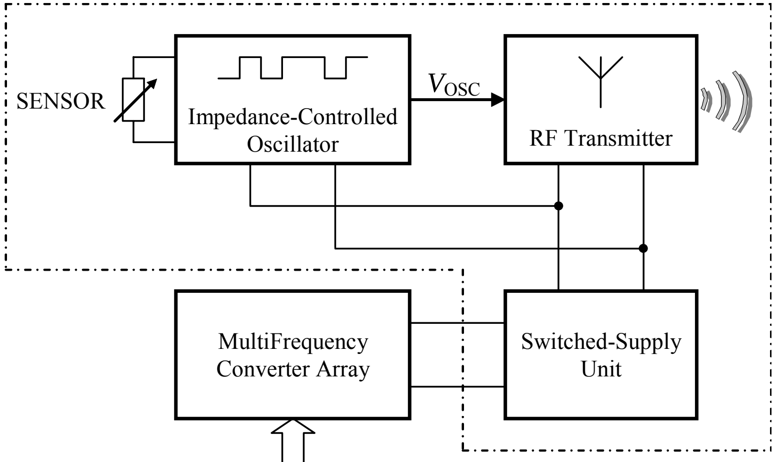
- Multiple differently-tuned converters combined to obtain a wider equivalent bandwidth:

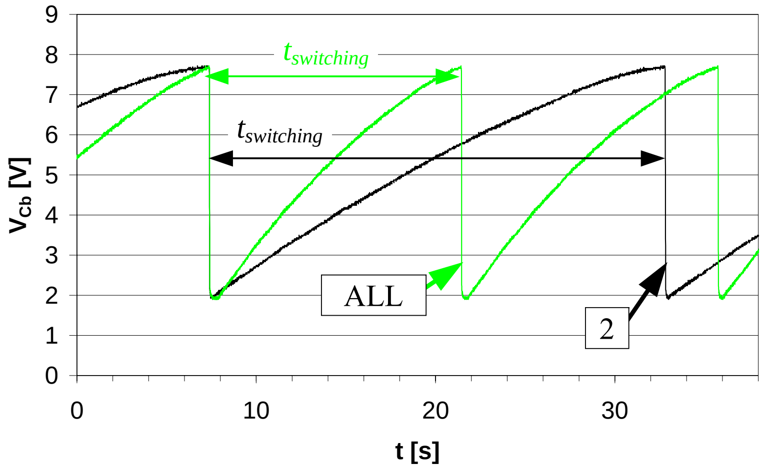




Measured frequency response.

- Bimorph commercial cantilevers (RS 285–784): 15 mm × 1.5 mm × 0.6 mm, m_1 = 1.4 g, m_2 = 0.7 g, m_3 = 0.6 g.





Measured voltage across the storage capacitor.

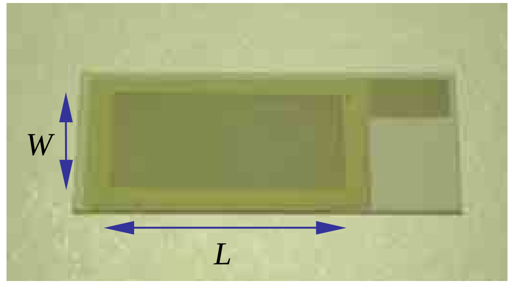
M. Ferrari *et al.*, *Sens. Actuat. A* **142**, 329-335 (2008).

Screen-Printed Piezoelectric Films

- Lead zirconate titanate (PZT) powder in polymeric binder
- Curing: (10 min @ 150°C)
- Electrodes: Ag polymeric ink
- Poling: (10 min @ 4 MV/m @130°C)

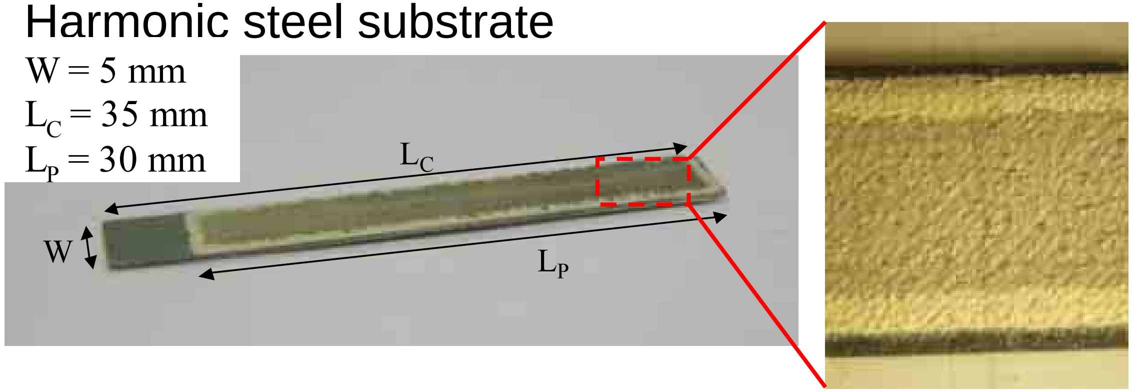
Alumina substrate

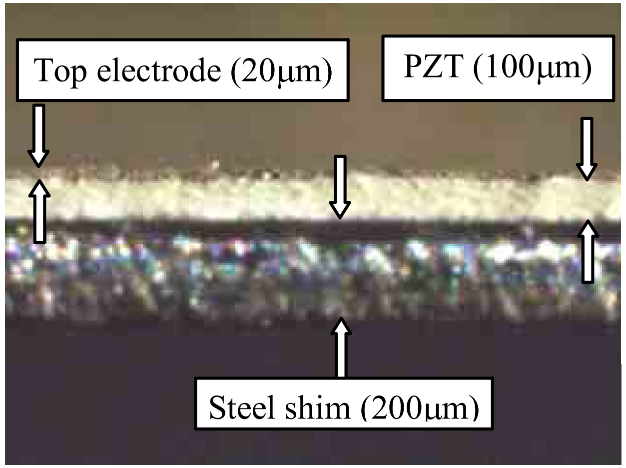
W = 18 mm
L = 31 mm
Film Thickness = 125 μm



Harmonic steel substrate

W = 5 mm
L_C = 35 mm
L_P = 30 mm



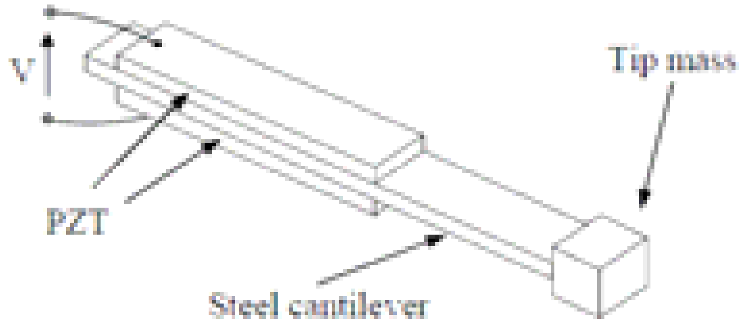


parameter	BULK CERAMIC	THICK FILM
rel. permittivity $\varepsilon^T/\varepsilon_o$	4100	100
density ρ [g/cm^3]	7.5	4.5
piezoelectric coeff. d_{33} [pC/N]	590	< 10

Piezokeramica-APC 856 powder
(soft material)

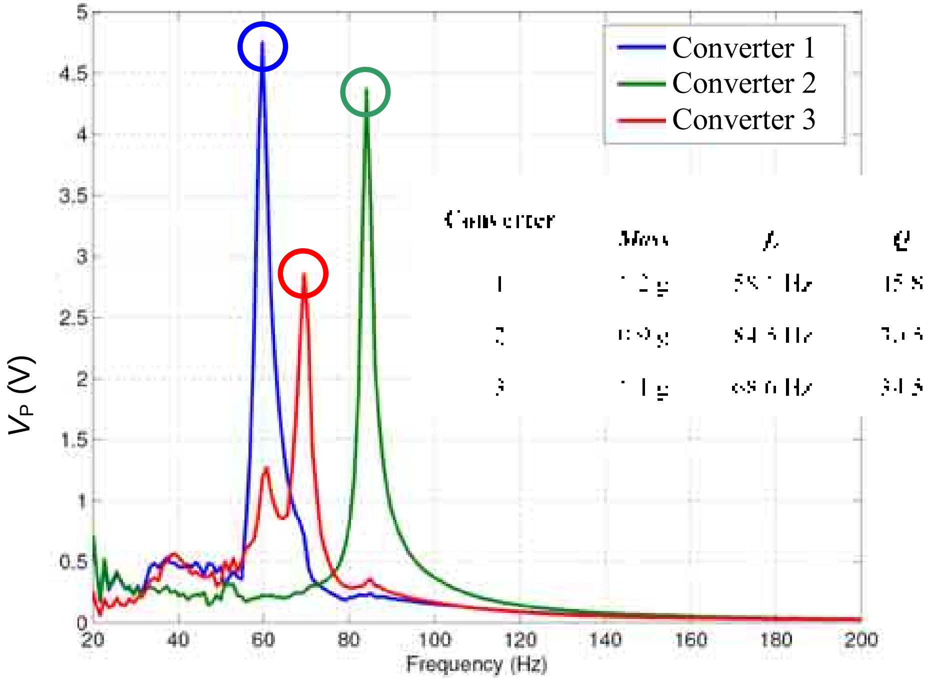
Steel Implementation of a MFCA

- Steel cantilevers (40 mm×5 mm×0.5 mm)
- Cured thickness of PZT film: 75 μm
- Series bimorph configuration

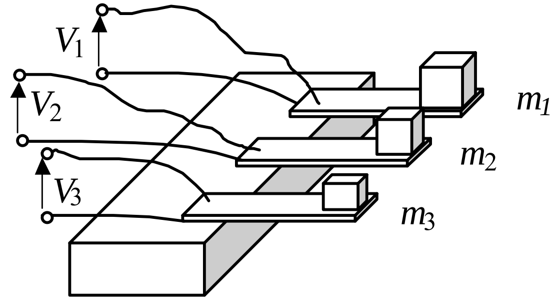


Internal impedance:
400 pF || 20 MΩ @ 100 Hz

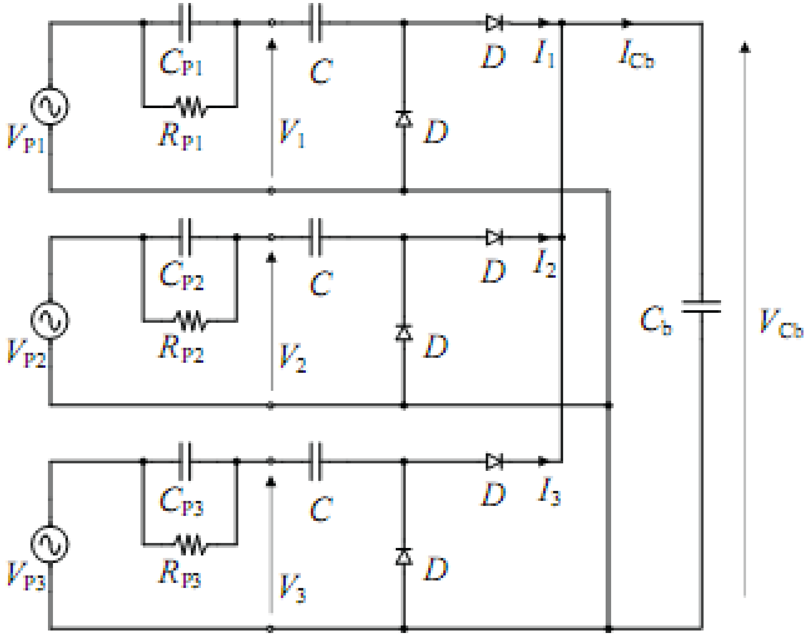
- Open-circuit voltages @ 1 g_{pk} acceleration



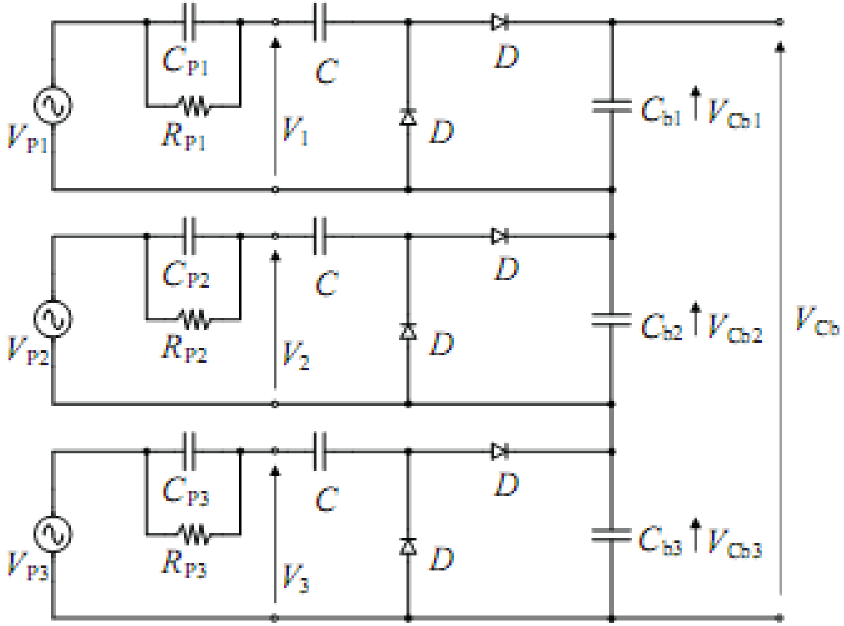
Output Combinations in a MFCA



- **Parallel-like combination:**
  - Rectified currents are fed to a single capacitor
- **Series-like combination:**
  - Rectified voltages on different capacitors are summed



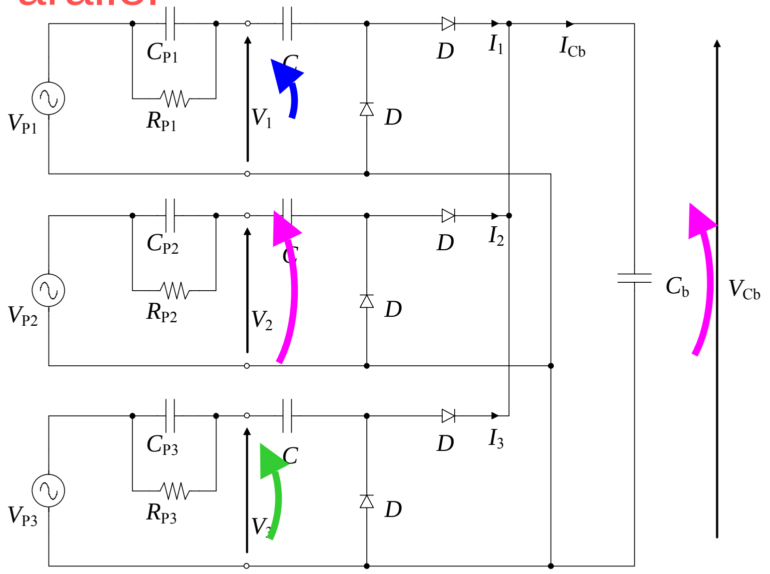
a) $I_{C_b}(t) = I_1(t) + I_2(t) + I_3(t)$



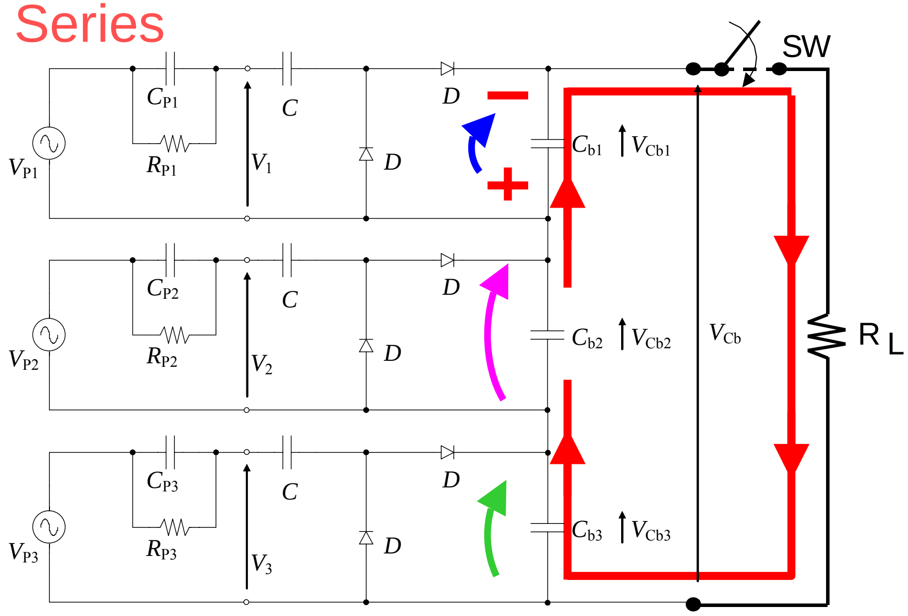
b) $V_{C_b}(t) = V_{C_{b1}}(t) + V_{C_{b2}}(t) + V_{C_{b3}}(t)$

Output Combinations in a MFCA

- Parallel



- Series

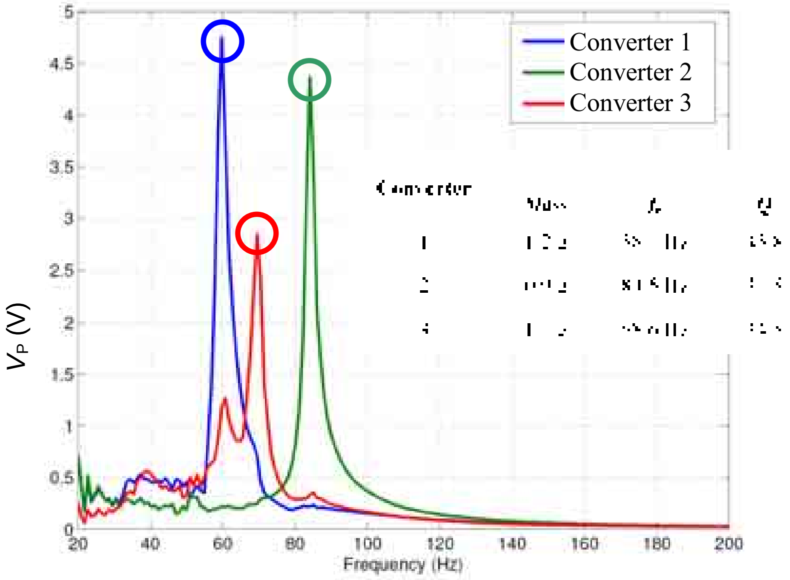


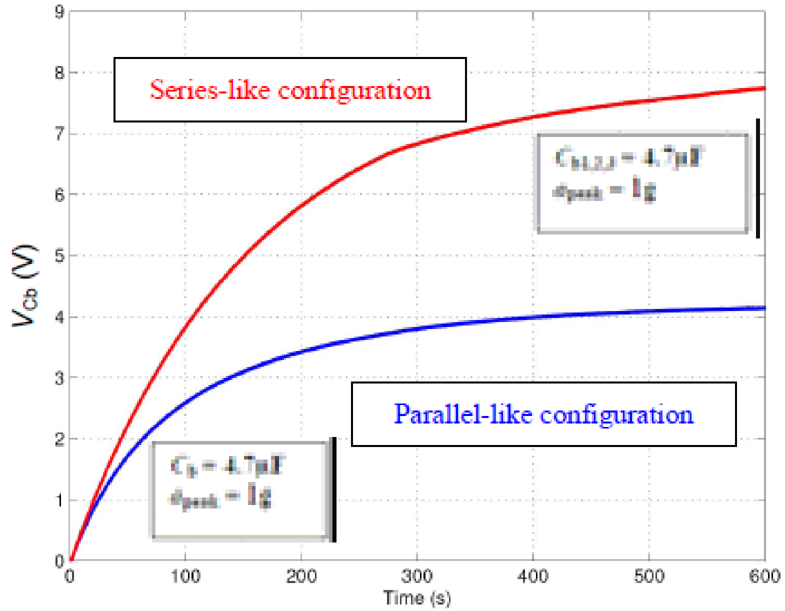
- The storage capacitor is charged prevalently by the converter with the highest instantaneous level
- The voltage is determined by the dominant converter
- Under wideband excitation, all the converters contribute to shorten the charging time

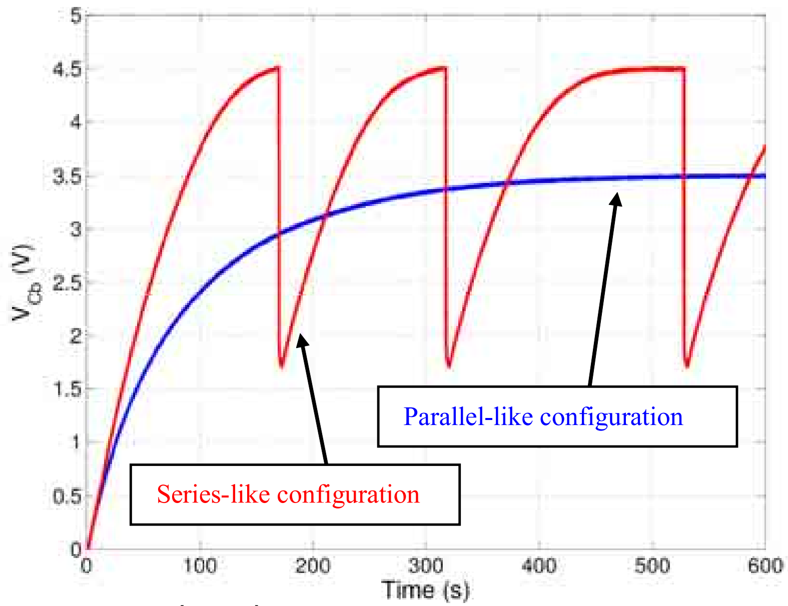
- Each storage capacitor is charged by the corresponding converter
- The voltage is given by the sum of the single voltages
- Inactive converters worsen energy transfer to the load due to charge redistribution upon switching

M. Ferrari *et al.*, *Proc. SENSORDEVICES-2010*, (2010).

Experimental Results on Steel MFCA







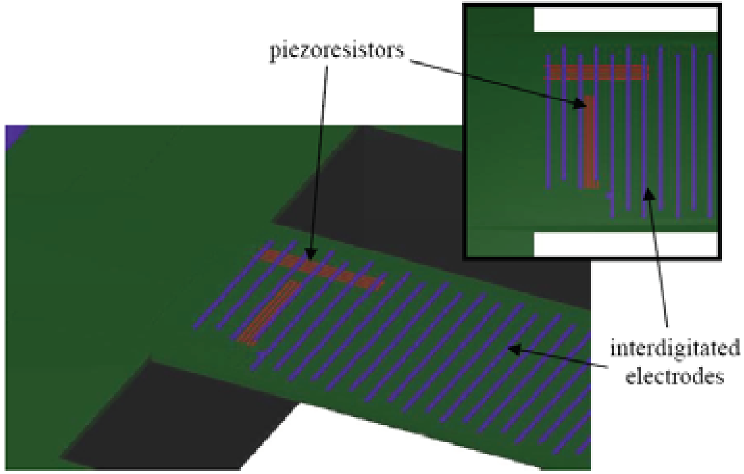
- The series-like configuration outputs a higher voltage at parity of excitation
- The series-like configuration reaches the threshold to trigger the RF transmission

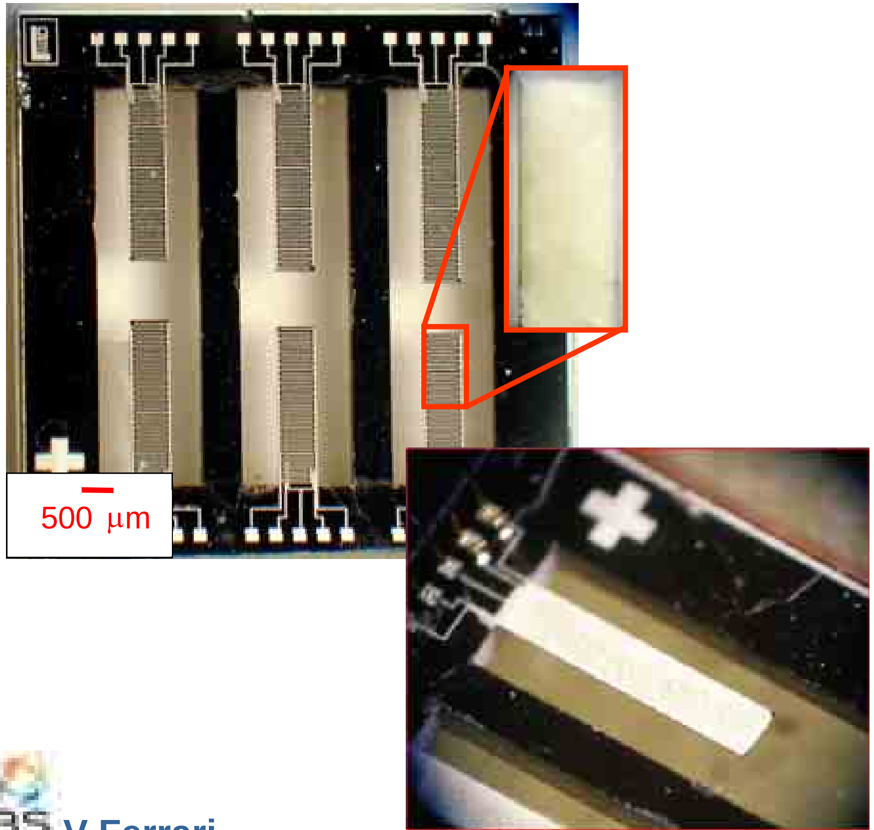
M. Ferrari *et al.*, *Proc. SENSORDEVICES-2010*, (2010).

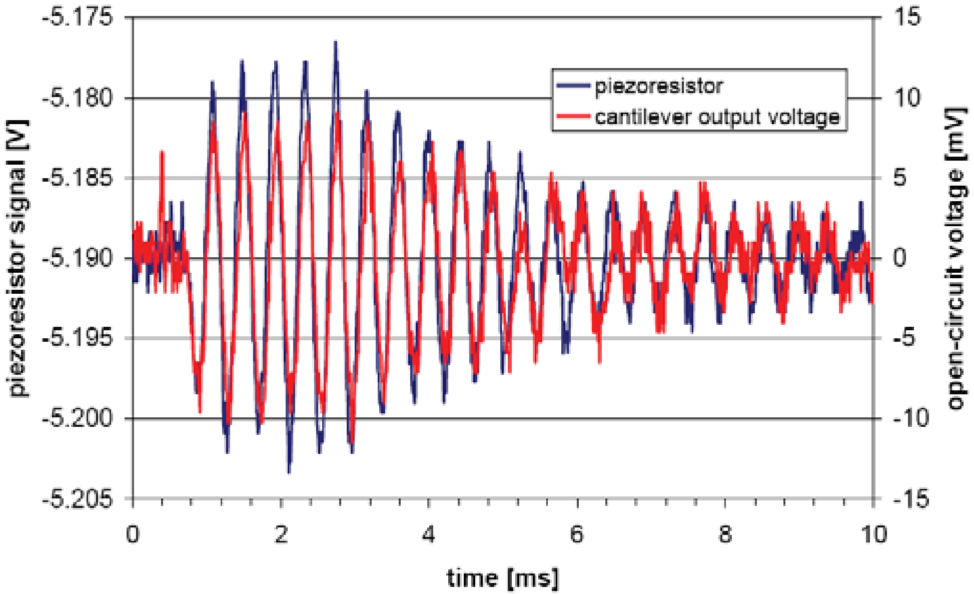
MEMS Implementation of a MFCA

- Design: University of Brescia
- Fabrication: CNM, Barcelona
- PZT paste: MEGGIT/Ferroperm

- Screen-printed PZT film
- IDT electrodes (d_{33} mode)

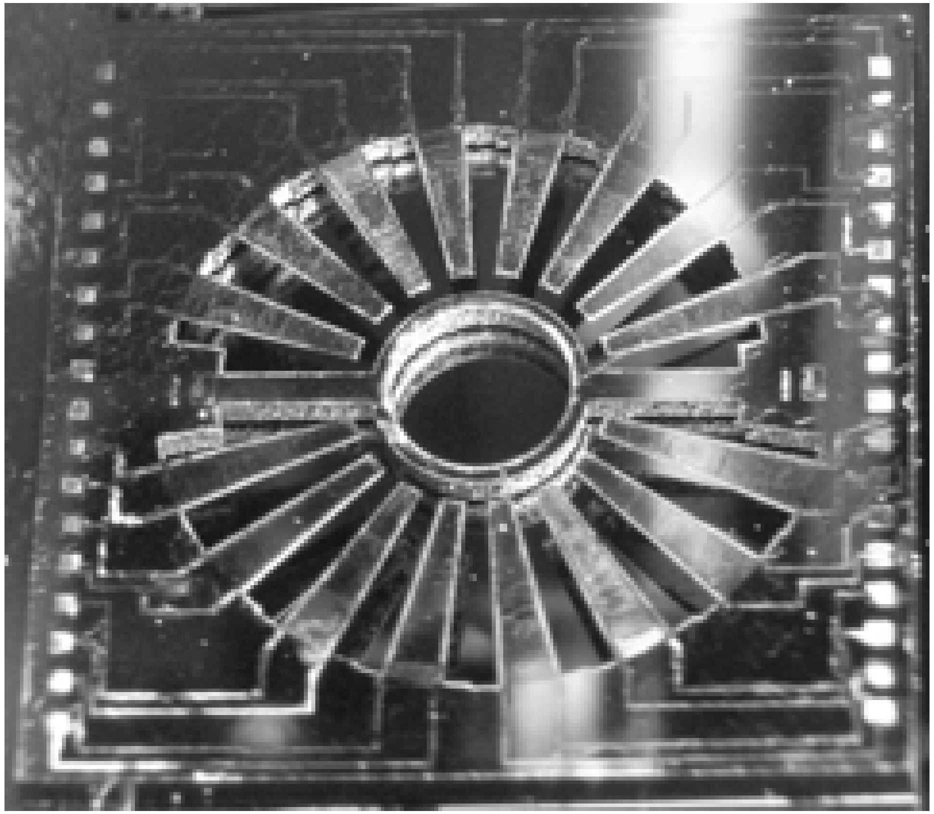


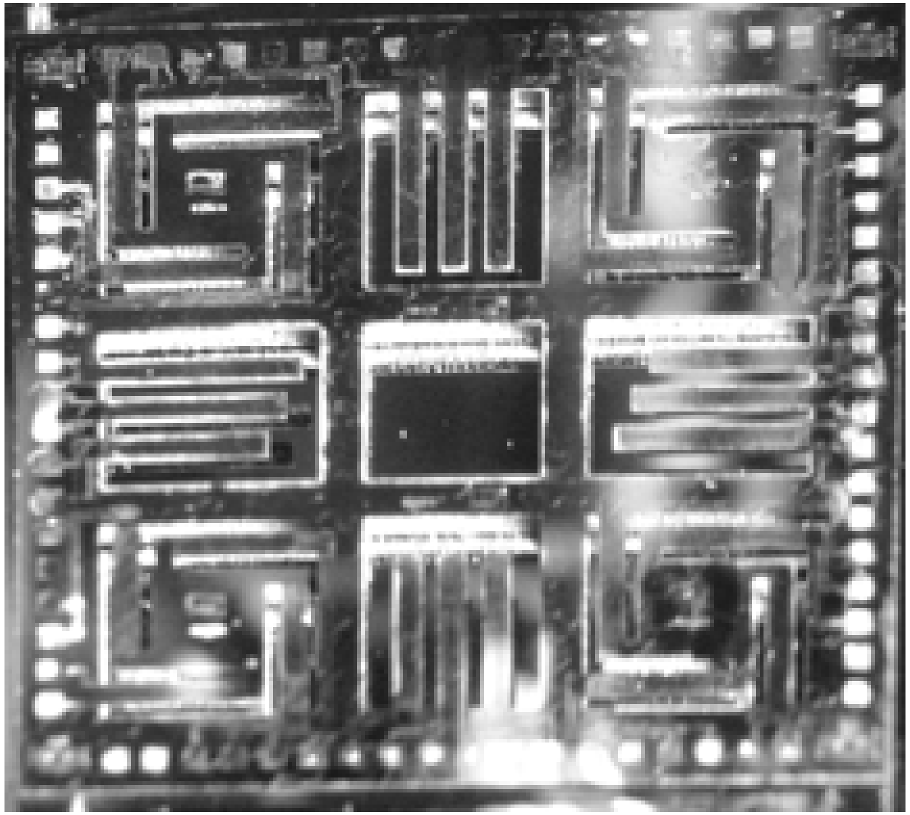




New Designs of MEMS MFCAs

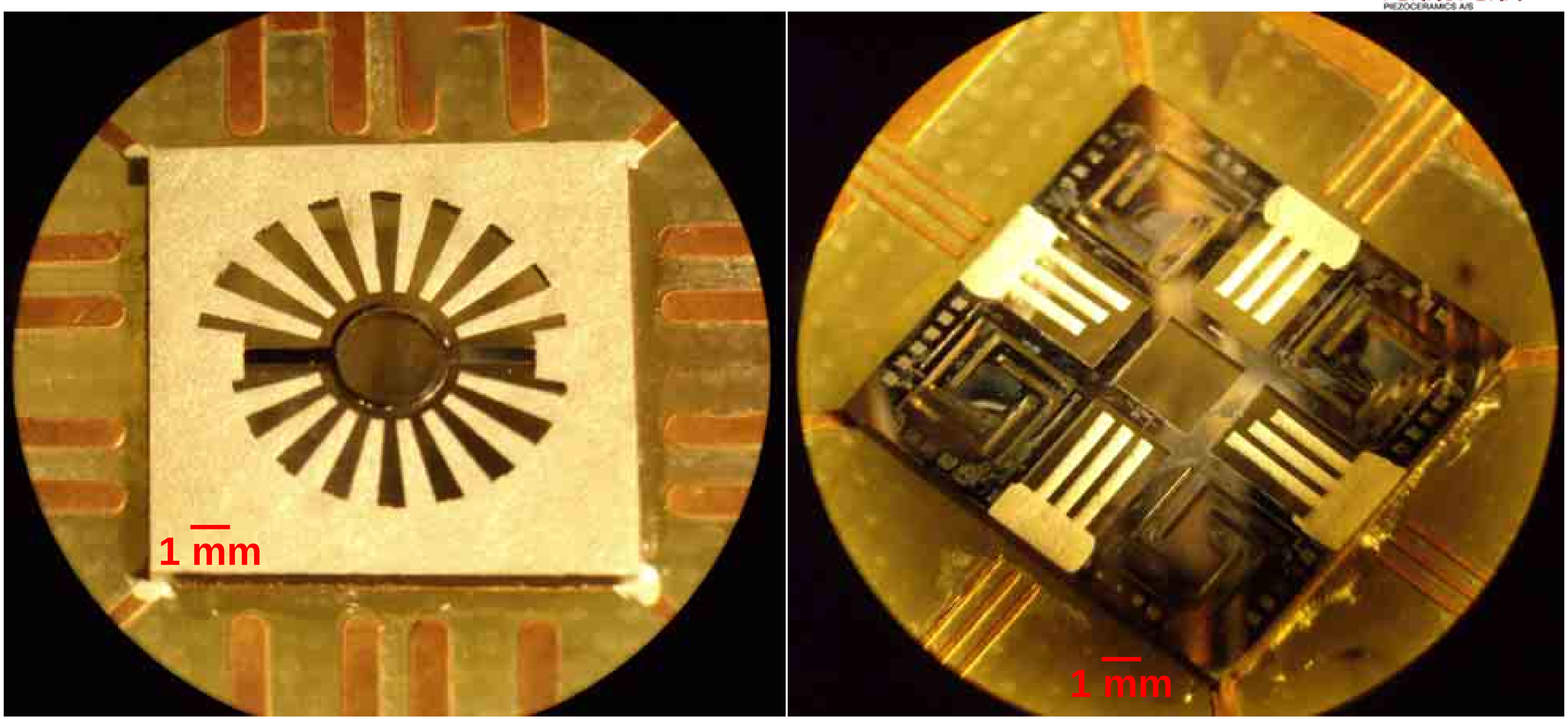
- Array of straight and tapered cantilevers
- Design: University of Brescia
- Fabrication: CNM, Barcelona
  - BE-SOI process (10 mm × 10 mm) die
  - Cantilever resonant frequencies: 4.5÷9 kHz - 3.5÷6.5 kHz





Deposition of Piezoelectric Film

- Sputtered Cr bottom electrode ($t_{Cr} \cong 0.5\ \mu m$)
- Screen-printed PZT film ($t_{PZT} \cong 30\ \mu m$)
  - PZT paste: MEGGIT/Ferroperm



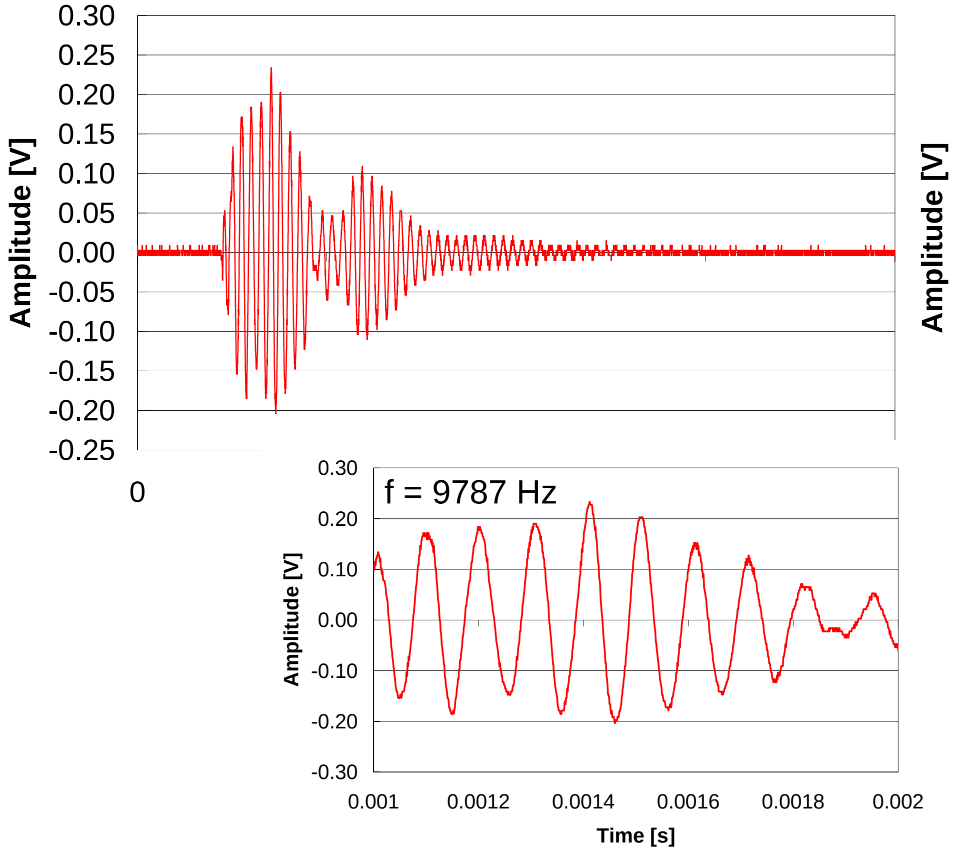
Top Electrode and Poling

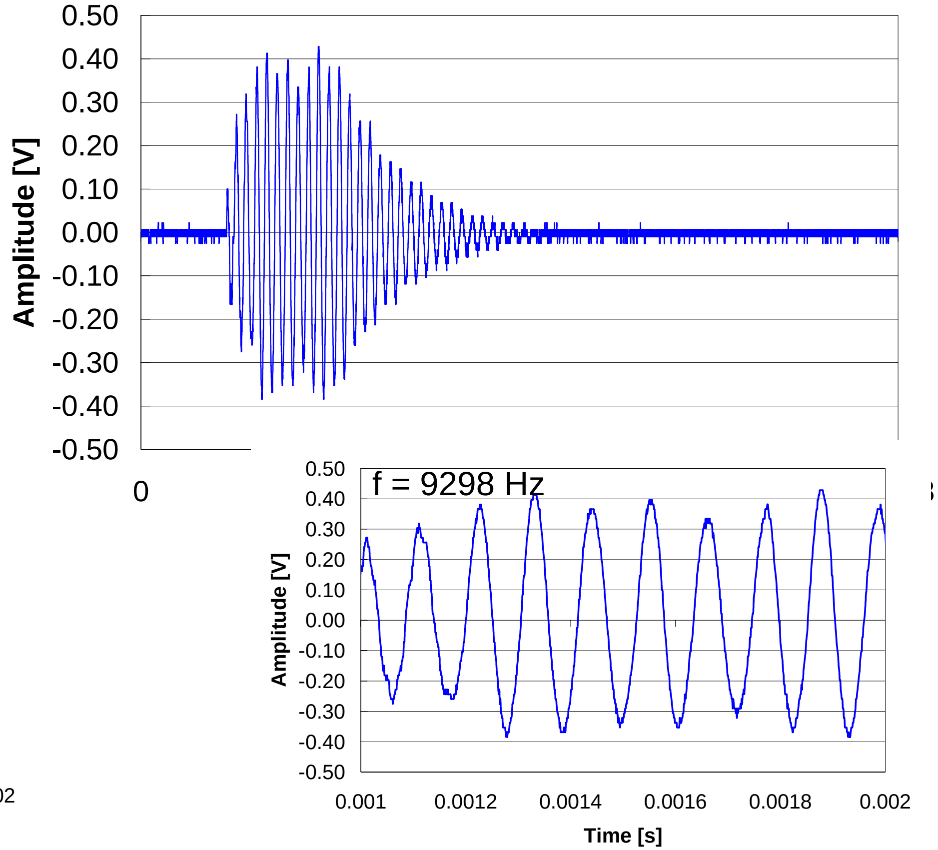
- Top electrode: direct writing* of Ag polymeric ink
- Poling: 120 V @100°C, 10 min

* Manual artwork in the first prototype

Preliminary Results

- Internal impedance @ 10 kHz:
  - $C_P = 7 \div 10$ pF; $R_P = 10 \div 30$ MΩ
- Impulse response tests:

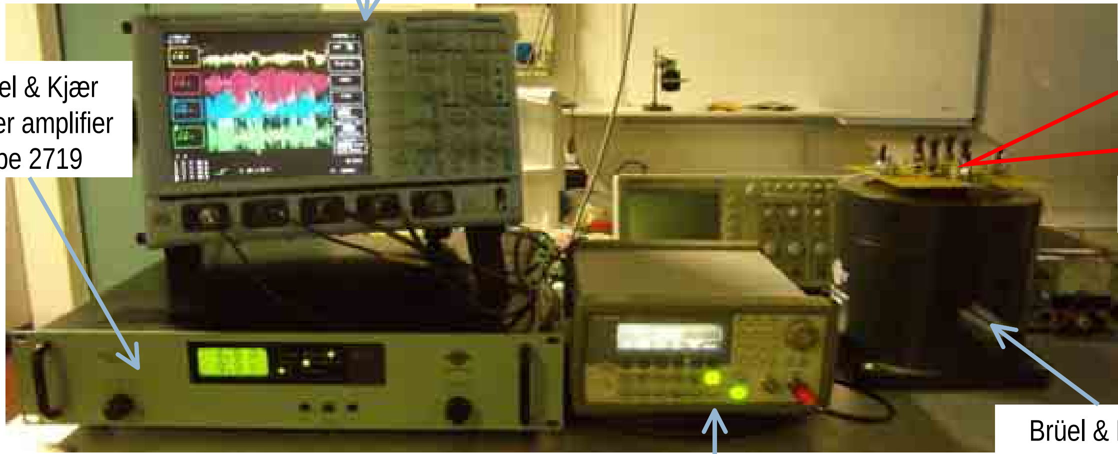


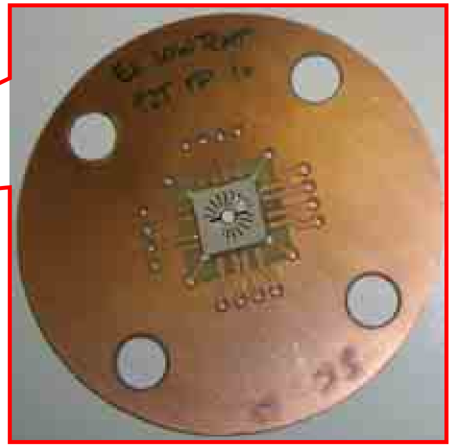


Preliminary Results

LeCroy
DSO LT374M

Brüel & Kjær
Power amplifier
type 2719

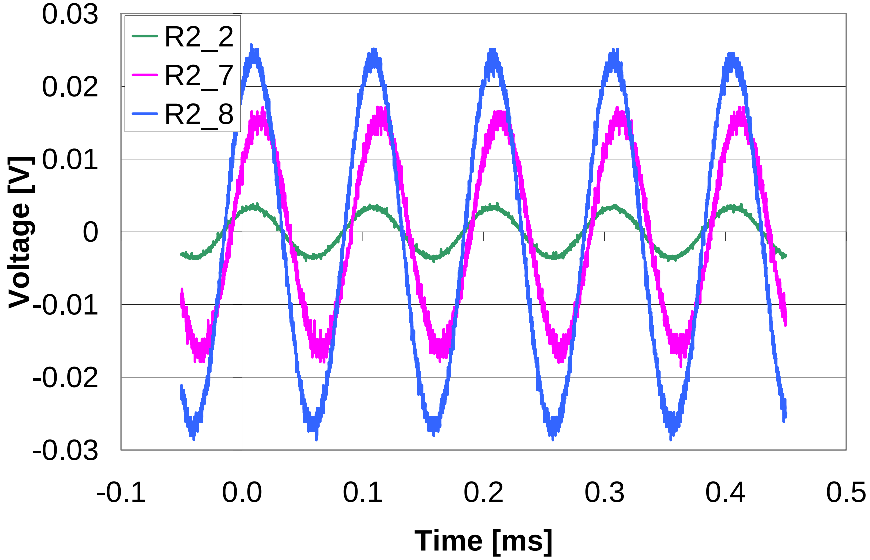




Agilent Waveform
generator 332200A

Brüel & Kjær
Vibration exciter
type 4808

- Sinusoidal excitation of the shaker $(a_{pk} \approx 1\ g)$
- Measurement of open-circuit voltage



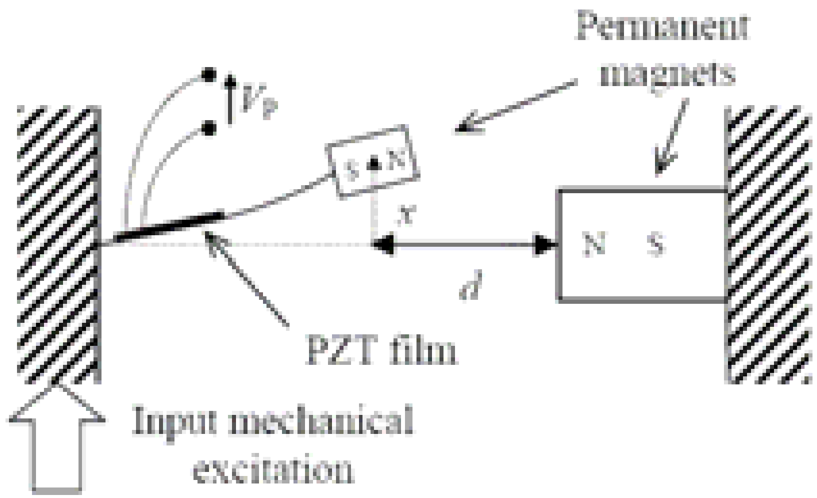
Contents

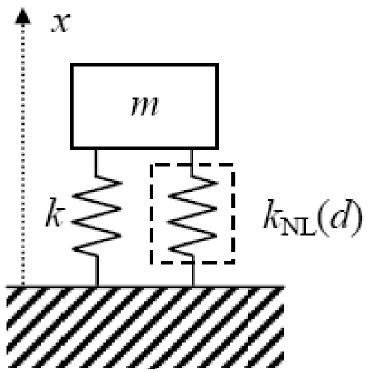
- Introduction
- Multi-frequency piezoelectric harvester arrays
- Nonlinear piezoelectric harvesters
- Conclusions

Nonlinear Converter

Collaboration with Univ. Catania (S. Baglio) and Univ. Perugia (L. Gammaitoni)

- **Bistability** is exploited to amplify displacement induced by **broadband vibrations**
- For decreasing values of d:
  - Quasi linearity
  - Nonlinearity
  - Bistability



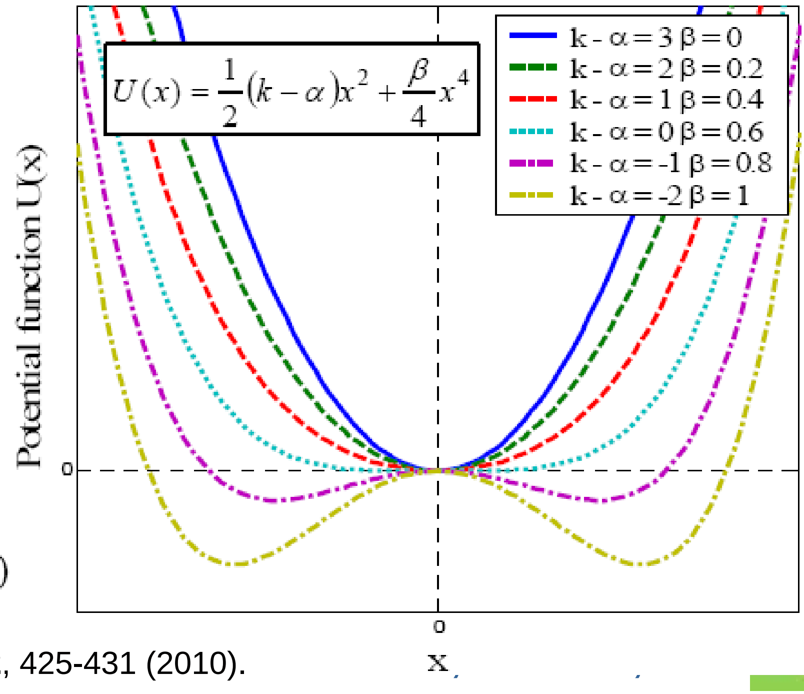


(a)

$$m\ddot{x} + (k - k_{NL})x = 0$$

$$k_{NL}(d) = \alpha - \beta x^2$$

$$F_{NL}(d) = \alpha x - \beta x^3$$

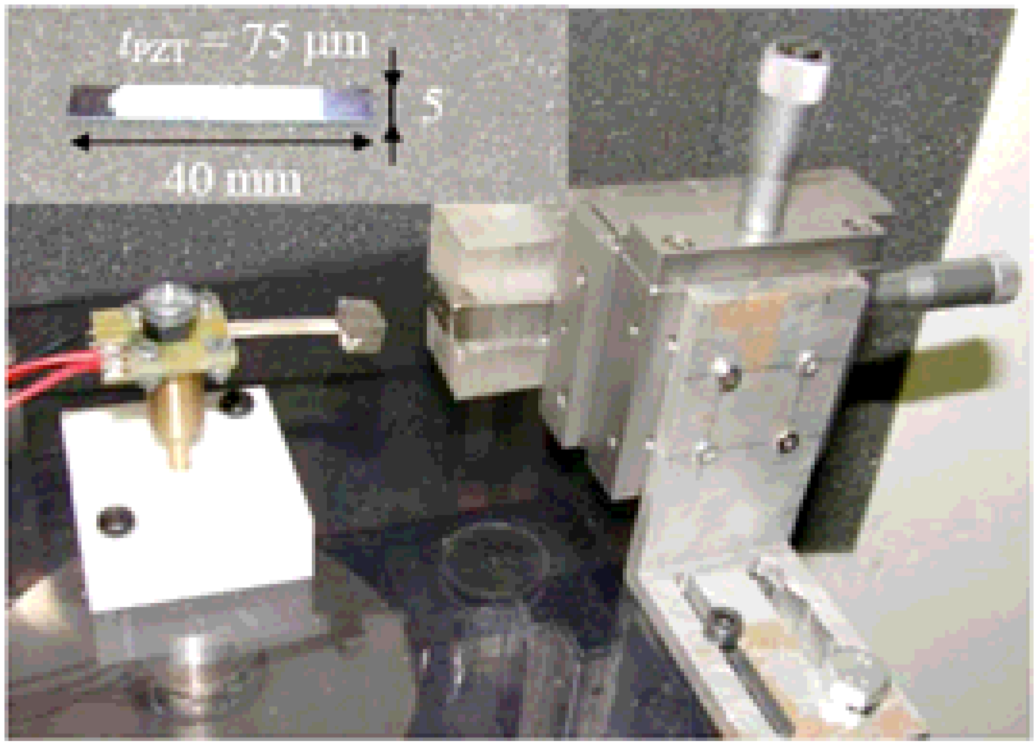


(b)

M. Ferrari *et al.*, *Sens. Actuat. A* **162**, 425-431 (2010).

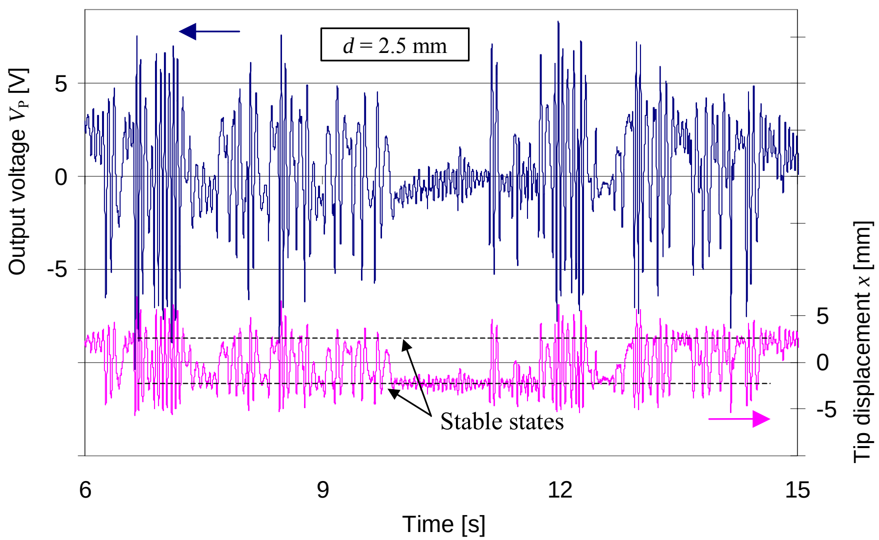
Nonlinear Converter: Experiment

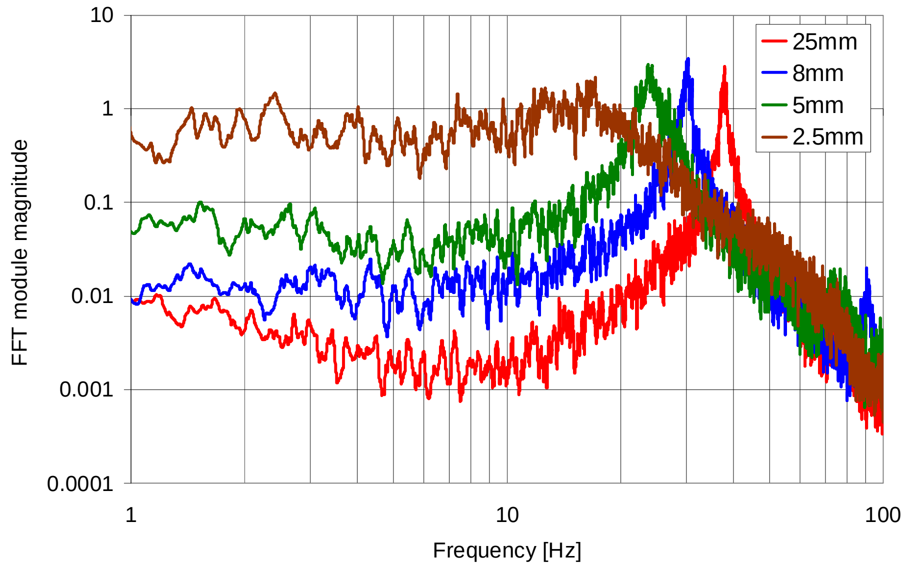
- Bimorph cantilever beam fabricated with:
  - Stainless steel substrate (thickness 200 μm)
  - Low-curing-temperature PZT films
- White-noise excitation filtered in the bandwidth 1-100 Hz



Nonlinear Converter: Results

- For suitably low gap d, jumps occur between stable states
- The output voltage spectrum broadens and V_{Prms} increases





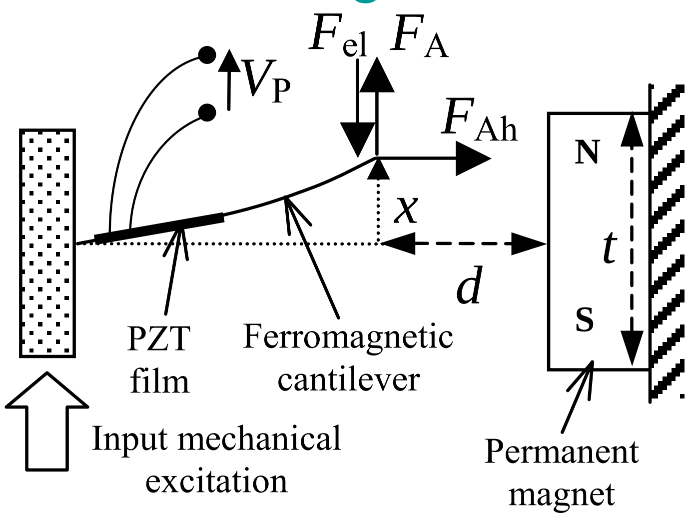
$a_{rms} = 0.3\ g$

Distance *d* [mm]	**rms output voltage V_{Prms}** [V]
25	4.27
5	6.11
2.5	7.99

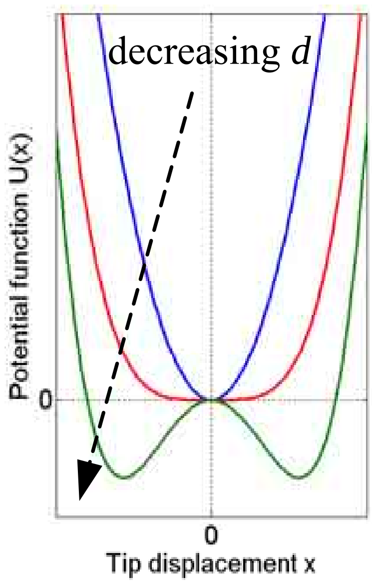
◆ Complex dynamics, see: S.C. Stanton *et al*., *Physica D* **239**, 640-653 (2010).

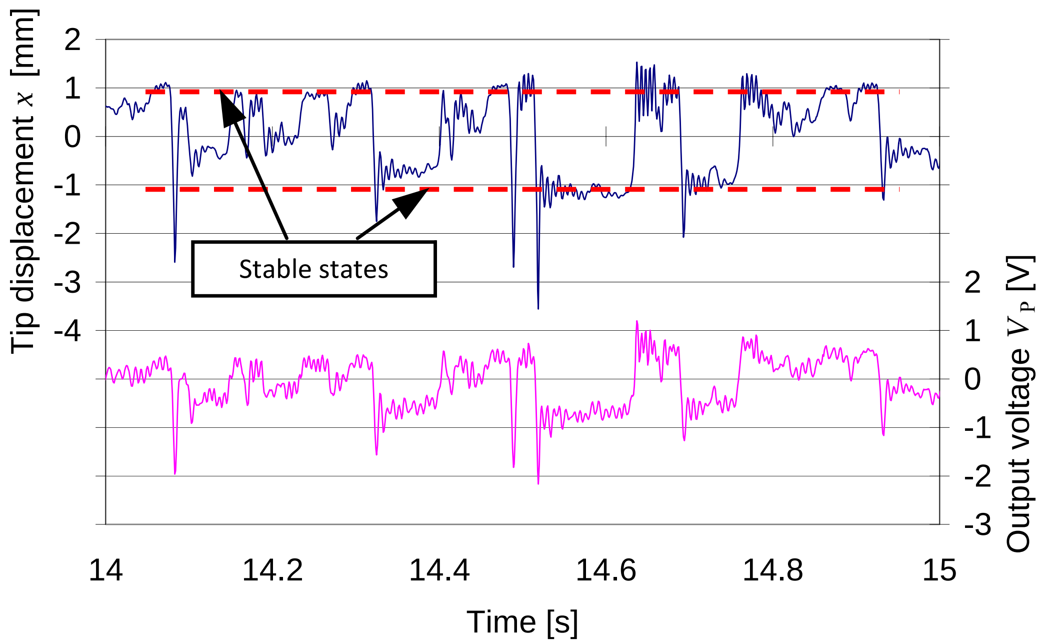
Nonlinear Single-Magnet Converter

- A ferromagnetic substrate is coupled to a fixed magnet



$$F_{Av} = \alpha x - \beta x^3 \quad F_{el} = -kx \quad U(x) = \frac{(k-\alpha)}{2} x^2 - \frac{\beta}{4} x^4$$



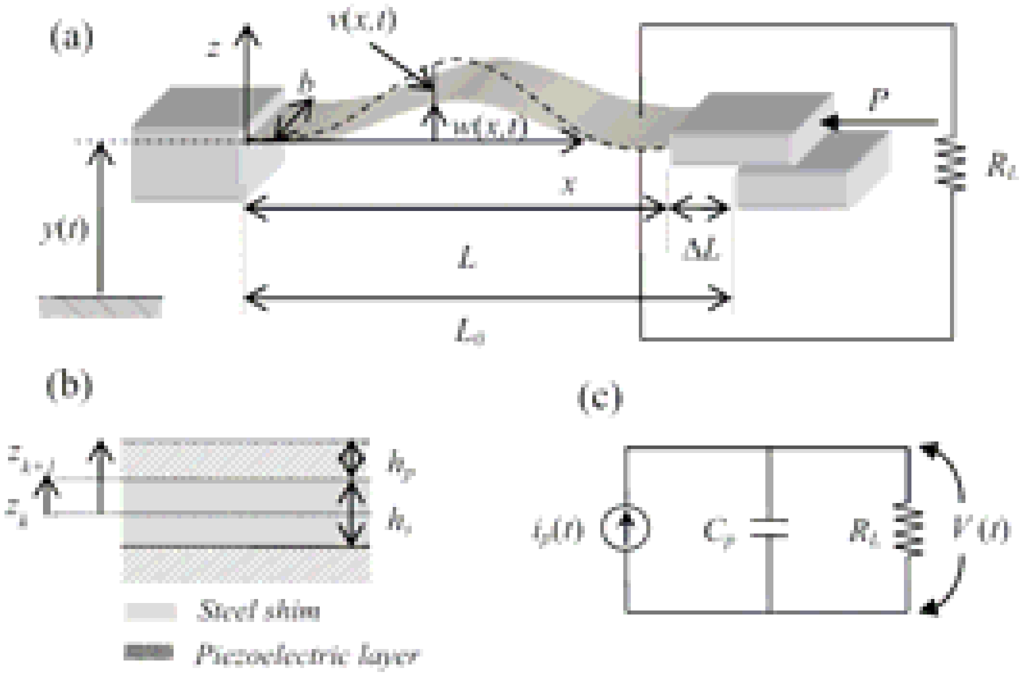


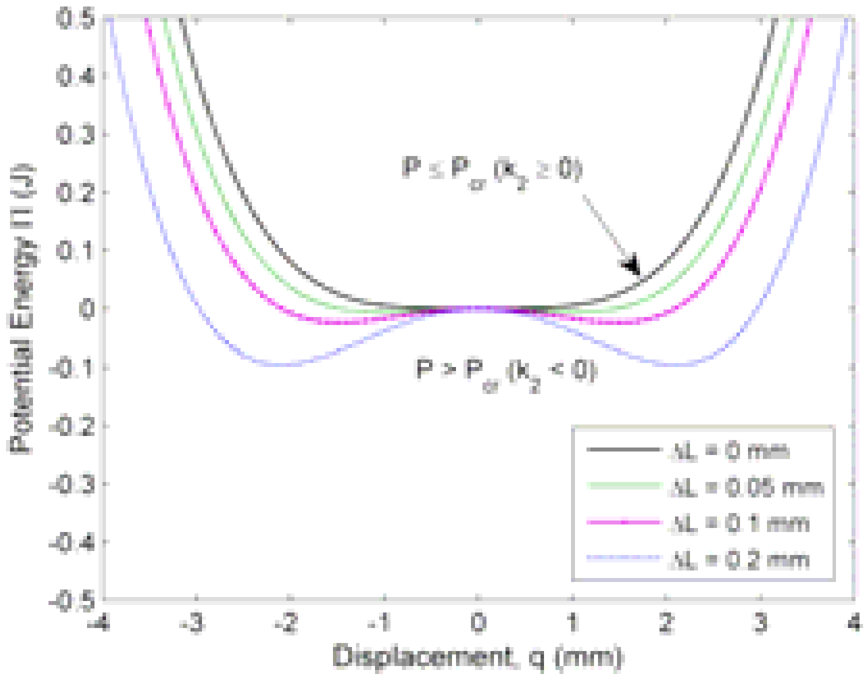
M. Ferrari *et al.*, *Sens. Actuat. A* **172**, 287-292 (2011).

Mechanically-Induced Bistability

Collaboration with Univ. Paris-Est (F. Cottone) and Univ. Perugia (L. Gammaitoni)

- An elastic beam compressed up to buckling shows bistability and double-well potential
- PZT layers on the beam perform enhanced energy conversion from bending vibrations





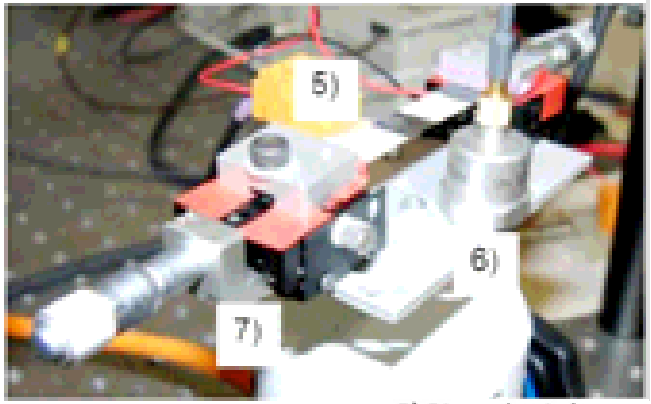
F. Cottone *et al.*, *Smart Mater. Struct.*, **21**, 035021 (2012).

Experimental Results

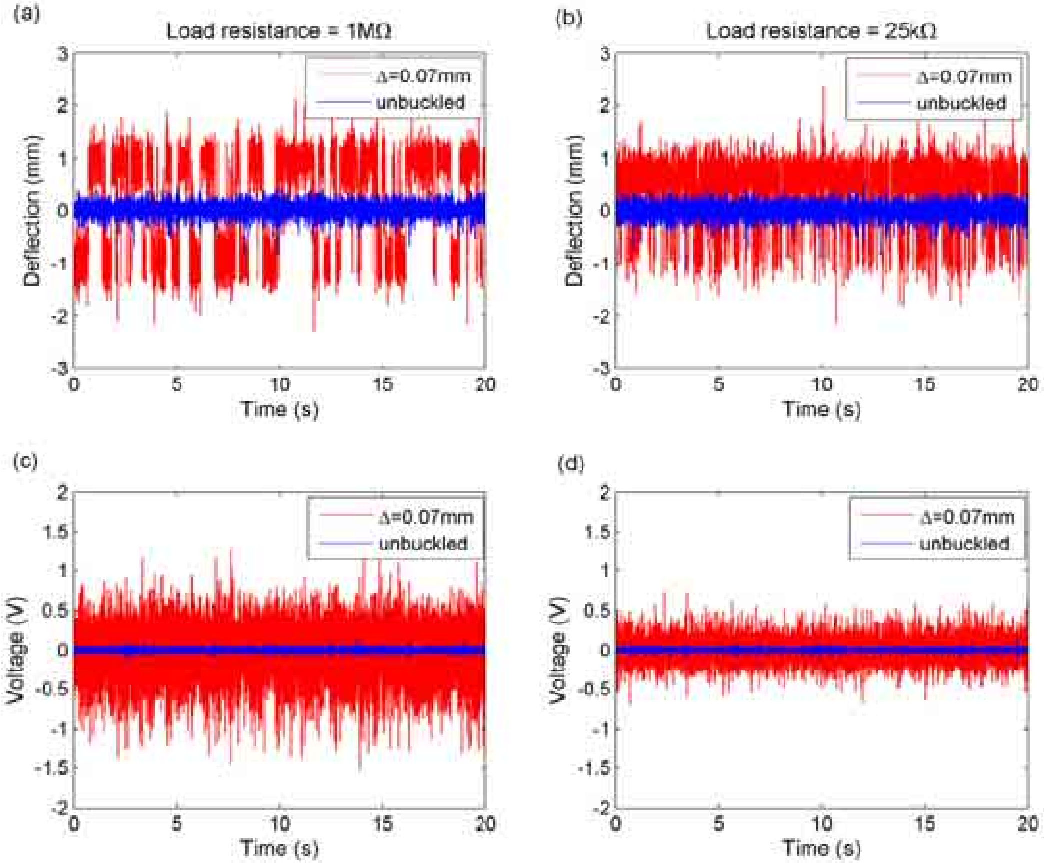
Collaboration with Univ. Paris-Est (F. Cottone) and Univ. Perugia (L. Gammaitoni)

Steel shim		Piezoelectric layer	
Parameter, symbol	Value	Parameter, symbol	Value
Material	Steel	Material	PZT film
Length, L_0	55 mm	Length of layers, L_p	55 mm
Width, b	11 mm	Length of electrodes, L_e	21 mm
Thickness, h_s	0.1 mm	Width, $b_p = b$	10 mm

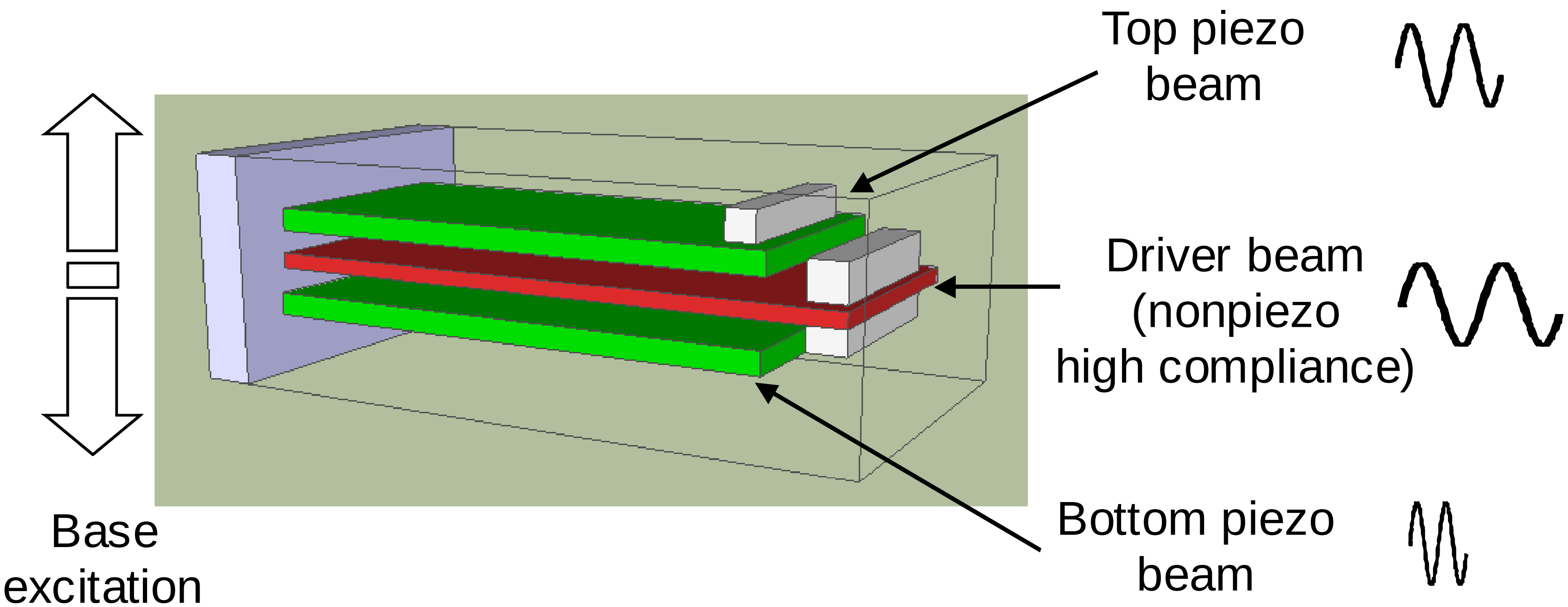
- PZT films screen printed on steel shims $(f_0 = 220\ \mathrm{Hz})$
- Shaker driven by Gaussian noise:
  autocorrelation time $\tau = 1$ ms;
  acceleration $1 \div 3\ g_{\mathrm{rms}}$



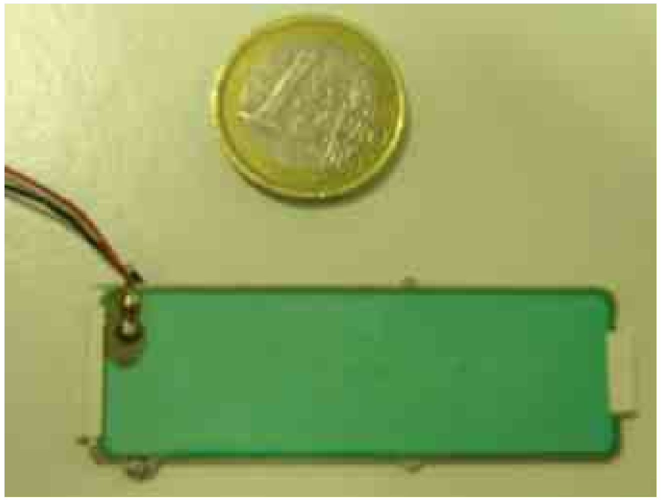
5) Piezoelctric beam
6) Accelerometer
7) Micrometric stage



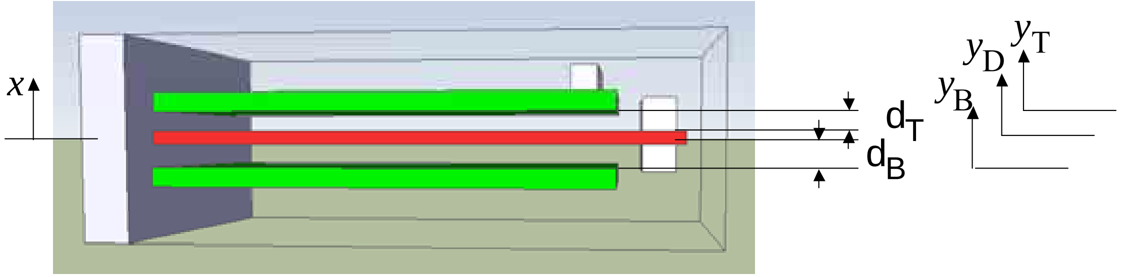
Impact-Enhanced Multi-Beam EH

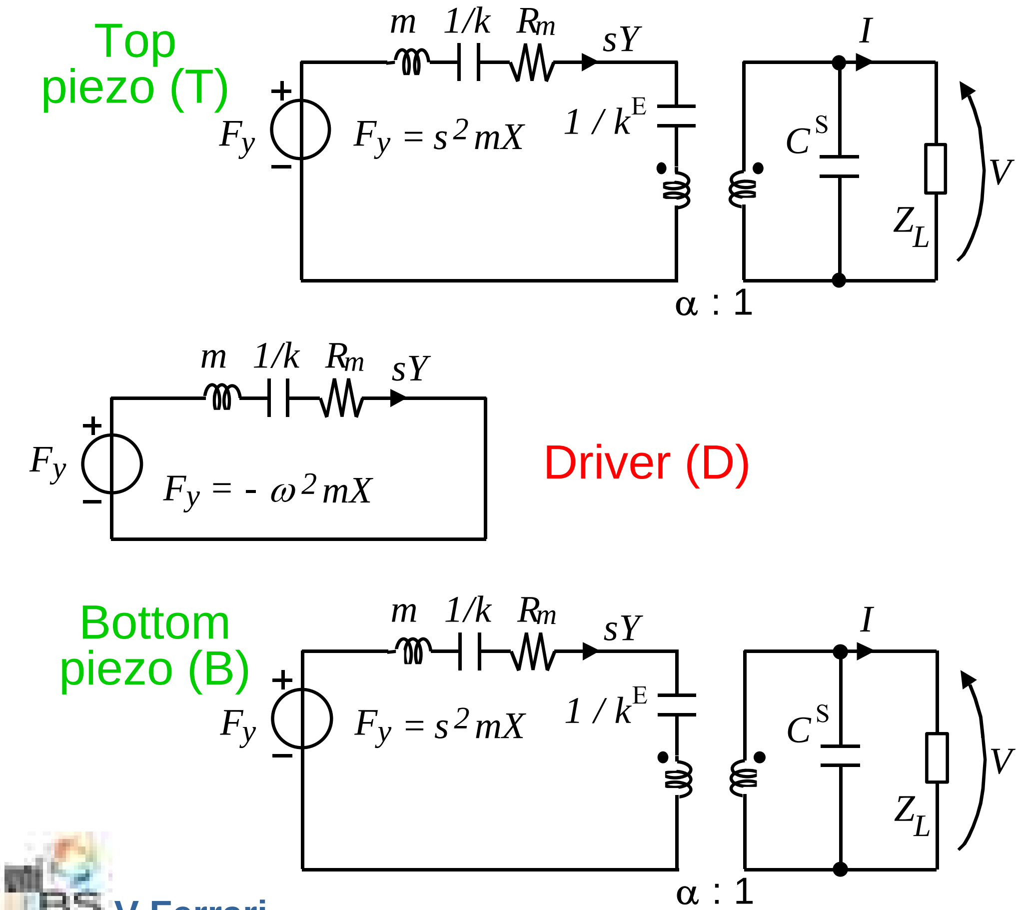


- PZT parallel bimorph on flexible steel
  - Beam dimensions: $(45 \times 19 \times 0.58)\ \text{mm}^3$
  - Internal impedance @ 100Hz: $C_P = 270\ \text{nF};\ R_P = 20\ \text{k}\Omega$



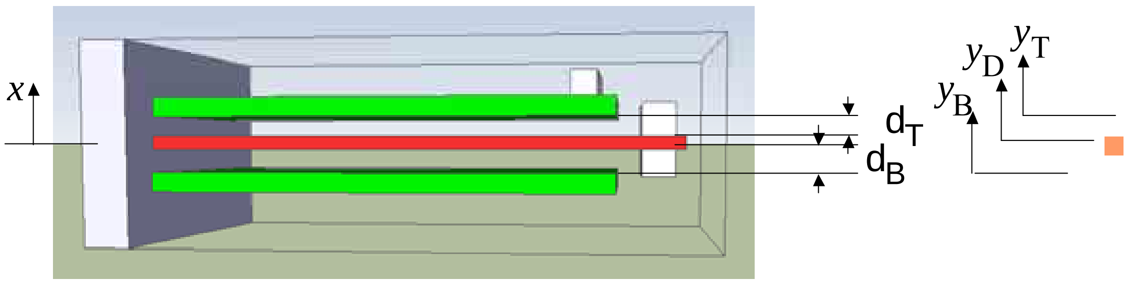
Modelling: Noninteracting Beams



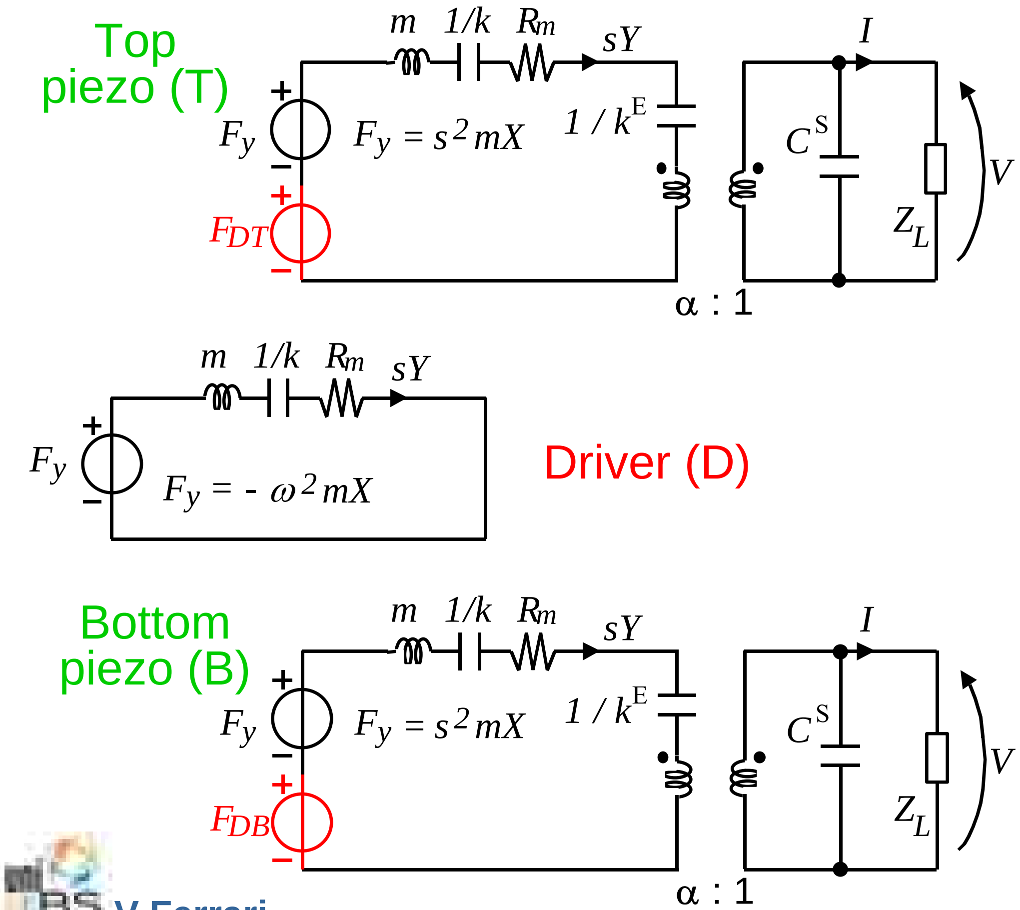


- T, B and D beams operate independently as uncoupled oscillators
- The outputs of T and B peak at the respective resonant frequencies
- Poor response at low frequency

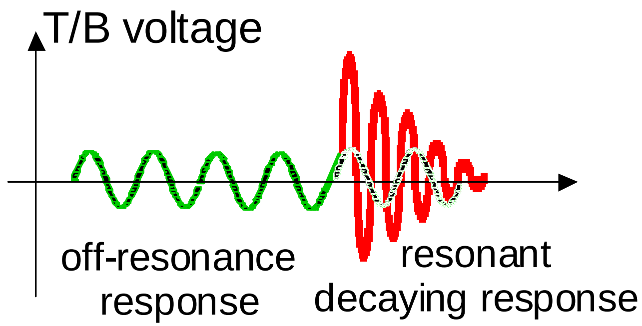
Modelling: Interacting Beams



- Assumptions:
  - Impulsive impact of D on T/B
  - Zero engaging time
  - No effect on D by T/B



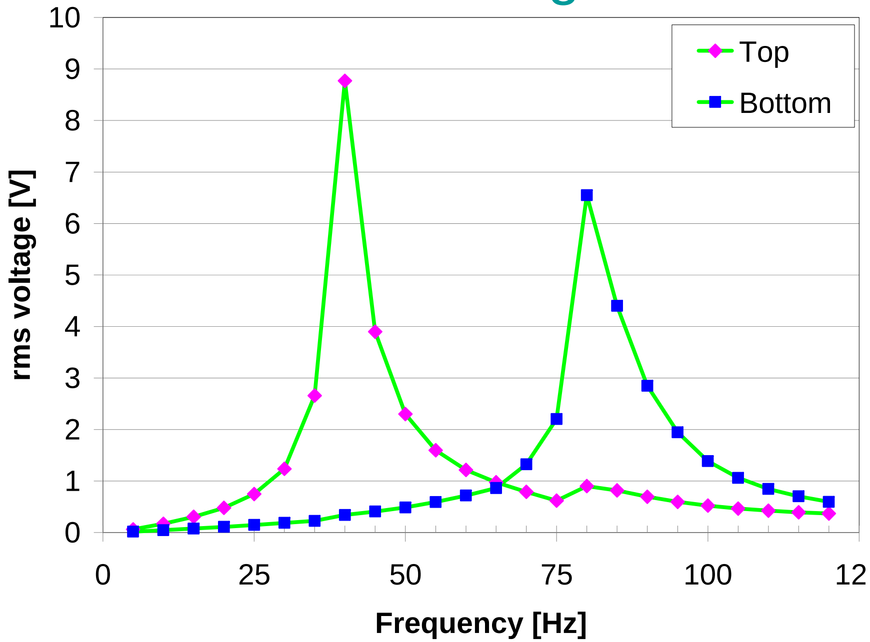
$$F_{DT,DB} = \begin{cases} 0 & d_{T,B} > 0 \\ f\left(\dot{y}_{DT,DB}\right) & d_{T,B} = 0 \end{cases}$$



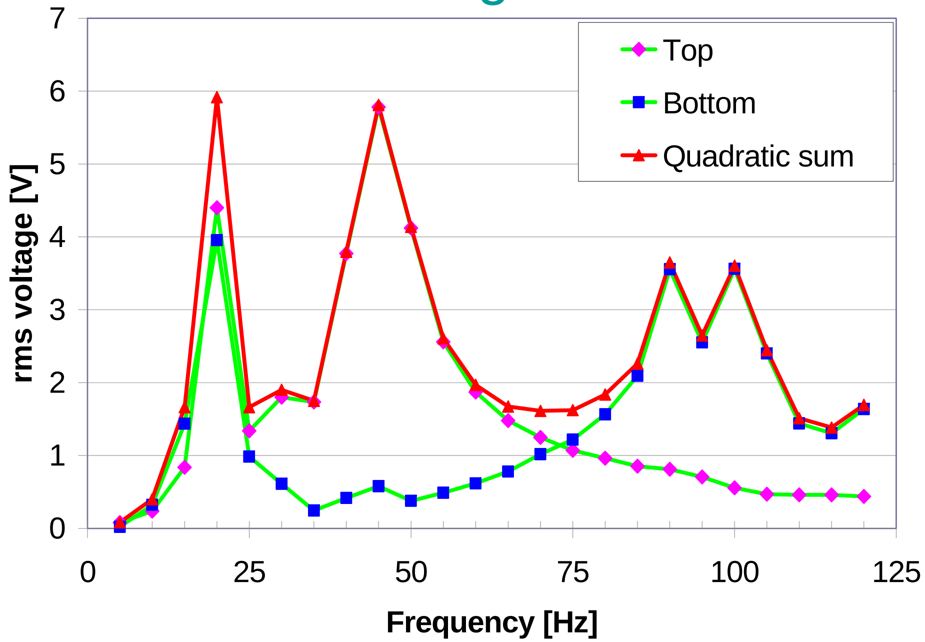
Experimental Results

- EH mounted on the shaker (Brüel & Kjær Vibration exciter type 4808)
- Swept-frequency excitation of the shaker (a_{pk} = 1 g @ 50 Hz)

◆ Noninteracting beams

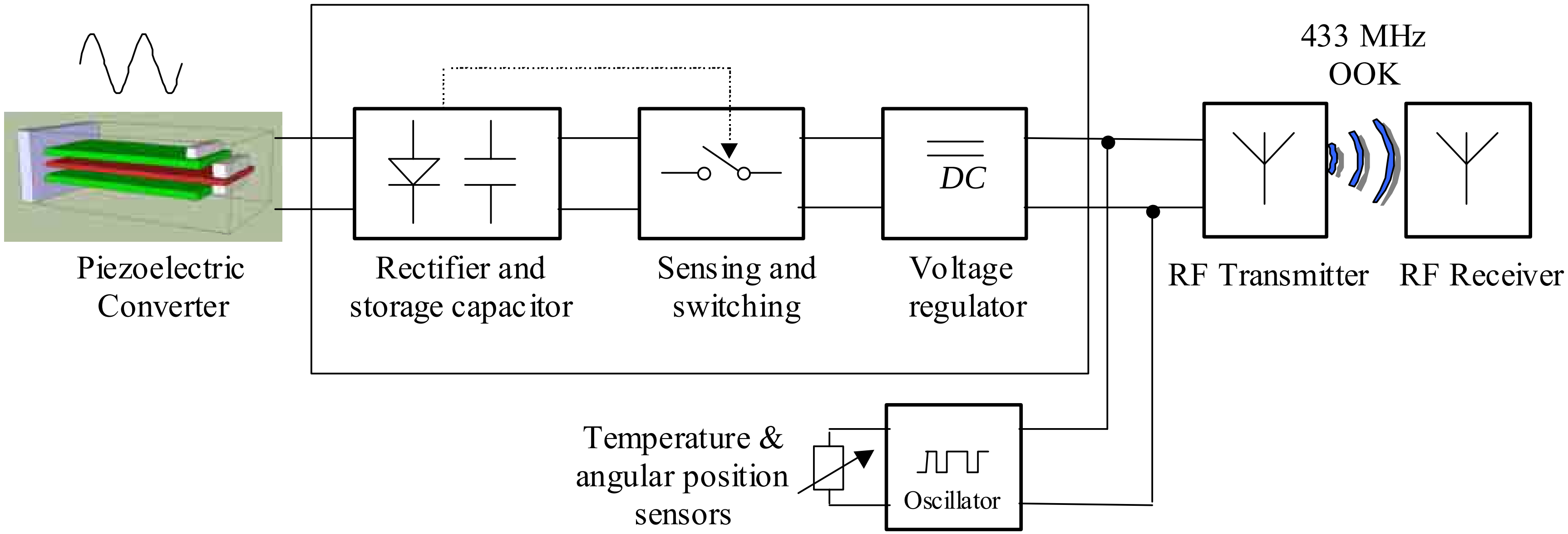


◆ Interacting beams



- Power on matched load: 1÷2 mW

Experimental Results

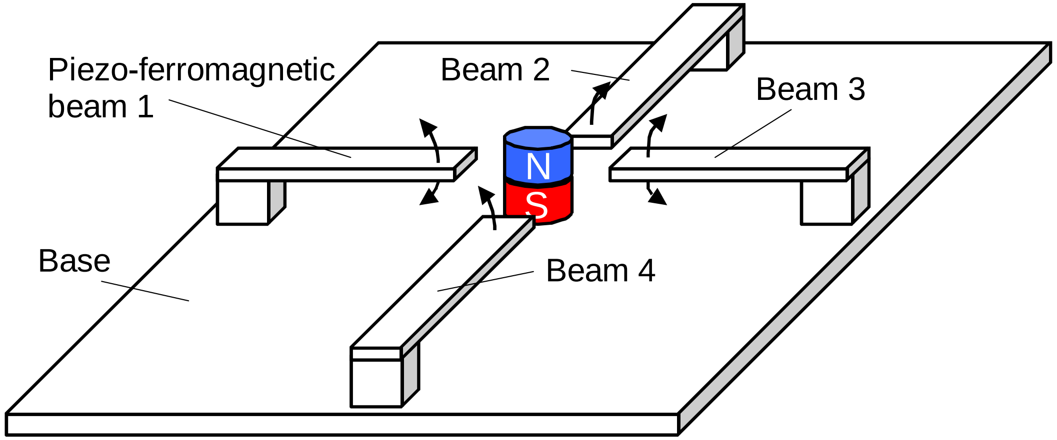


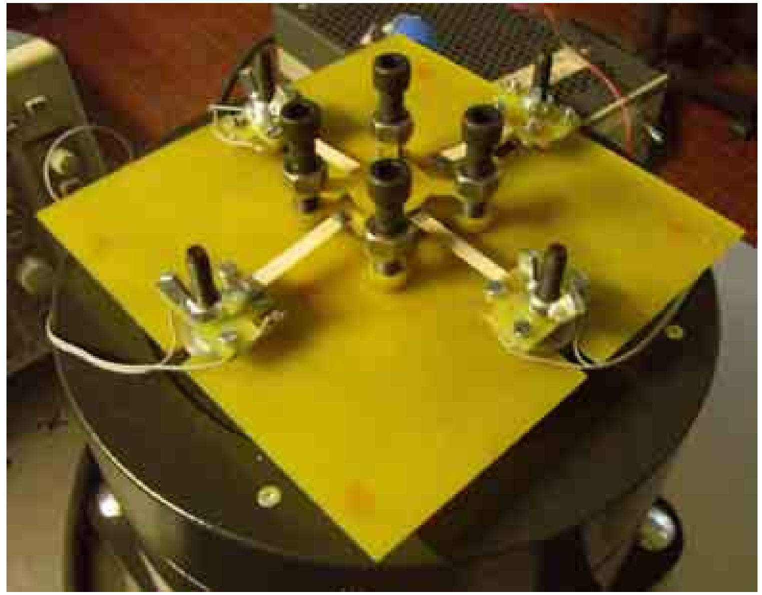
- Handheld EH intentionally shaken
- RF transmissions start after 10 to 15 s and repeat every few seconds under moderate to forcible shaking

F. Cerini
D. Roncali
University of Brescia

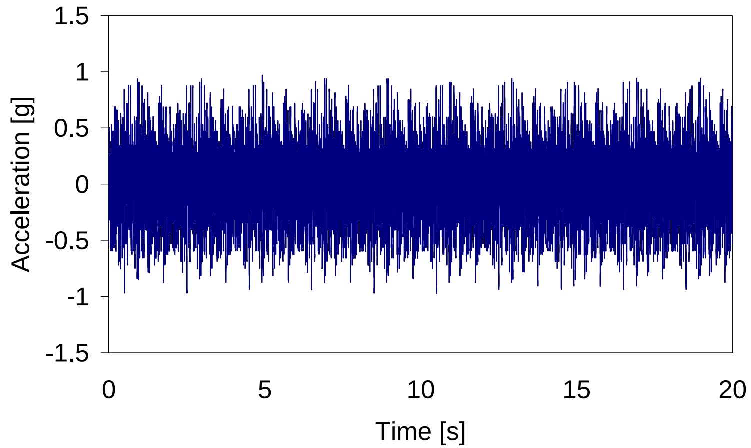
Nonlinear MultiFrequency Array

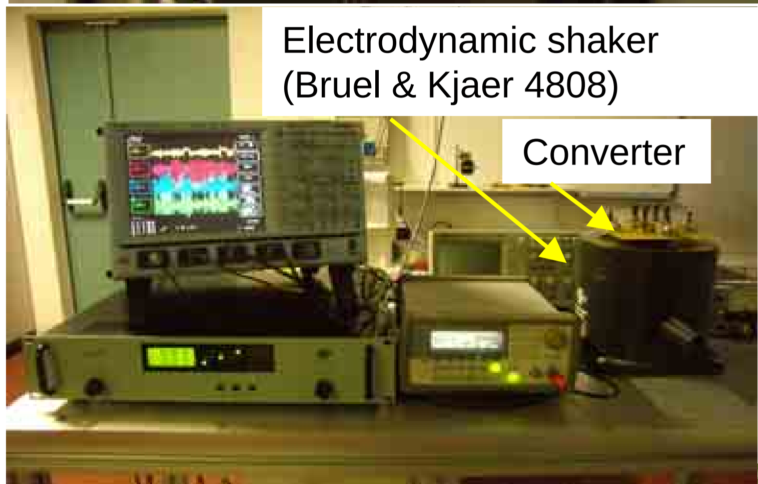
- MFCA and NL concepts merged into a compact configuration
- The beams have different frequency responses





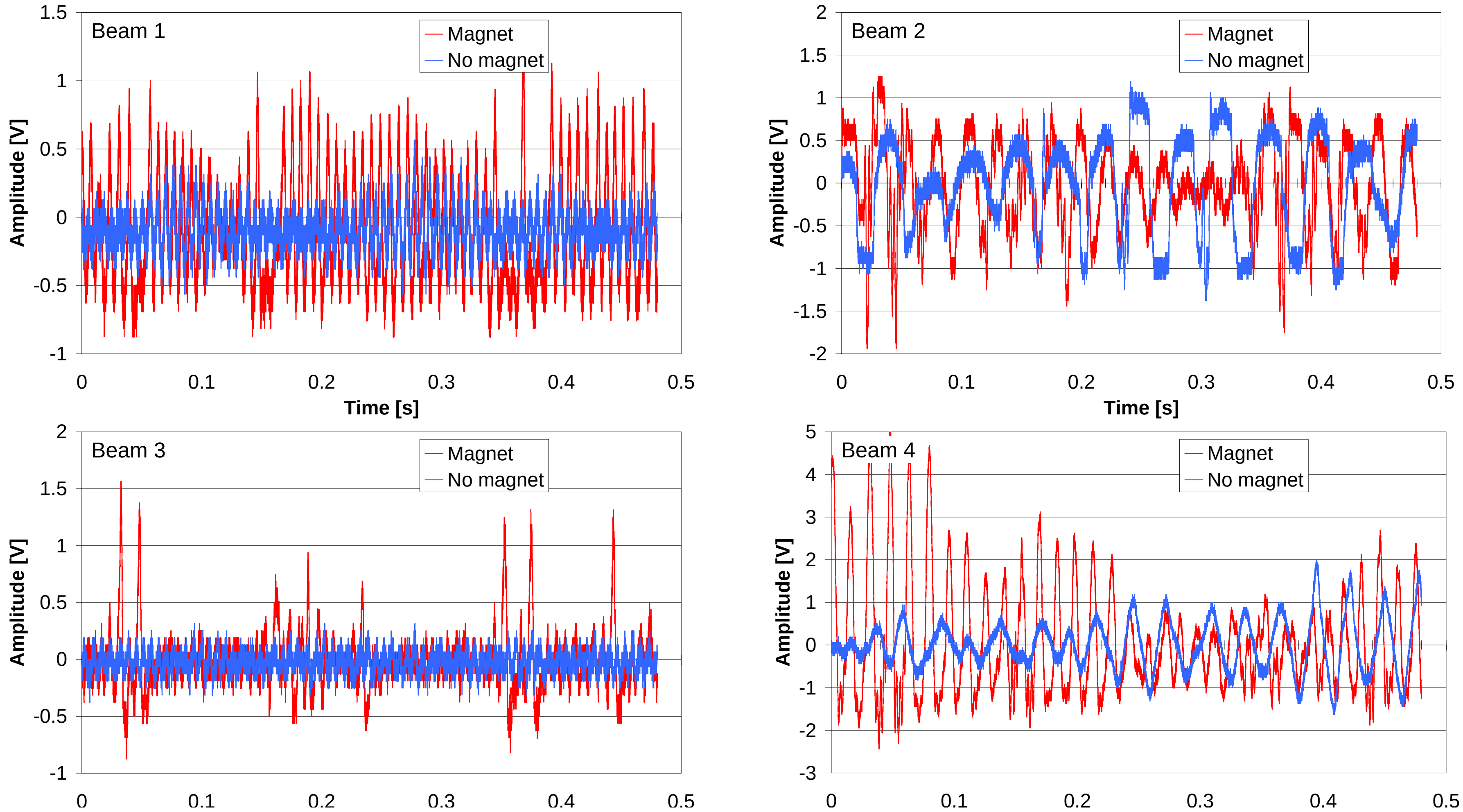
Parameter	Beams 1, 3	Beams 2, 4
Steel thickness [μm]	200	100
Tip mass	no	yes
Res. frequency [Hz]	150	30





Experimental Results

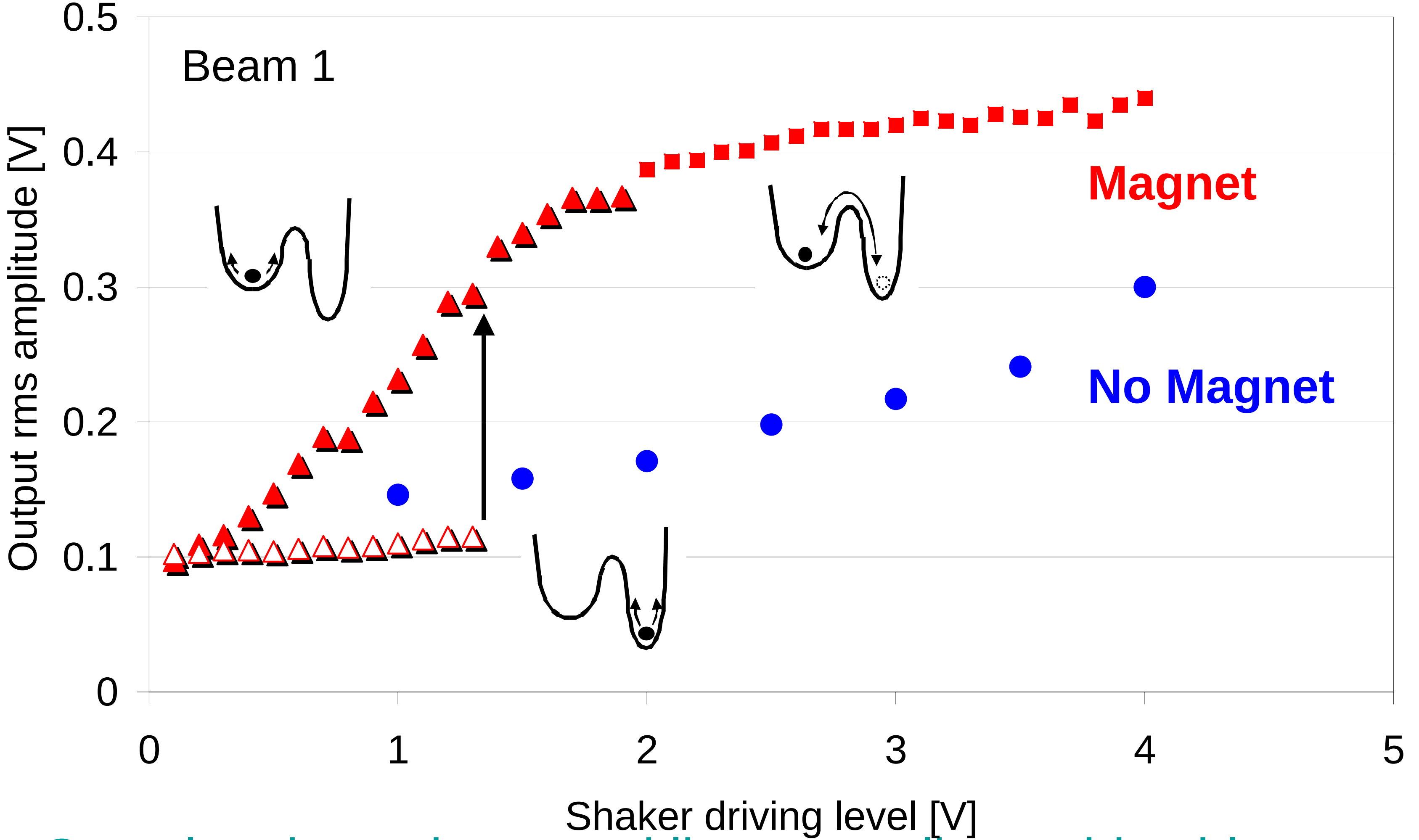
- Typical responses with and without the magnet



- Complex dynamics: quasi linear, nonlinear, bistable
- In all cases the magnet increases the rms output

Experimental Results

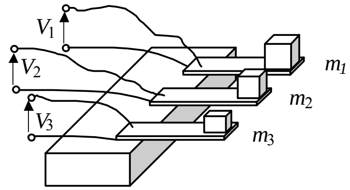
- Typical responses with and without the magnet



- Complex dynamics: quasi linear, nonlinear, bistable
- In all cases the magnet increases the rms output

Summing Up

- **Linear MFCA harvesters:**

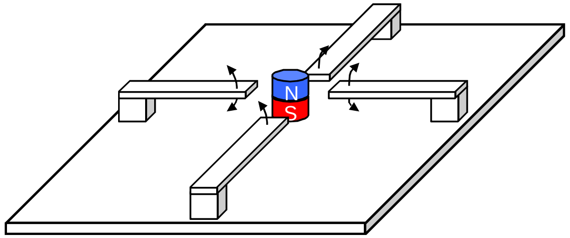


  - ☺ Bandwidth is not amplitude-sensitive
  - 😐 Good performances with multi-tone excitations
  - ☹ Bandwidth is limited by the resonances of the array elements

- **Nonlinear (NL) harvesters**

  - ☺ Bandwidth exceeds the range of linear resonances
  - 😐 Good performances with random excitations
  - ☹ Sufficient amplitude is needed for bandwidth expansion

- **NL- MFCA harvesters:**



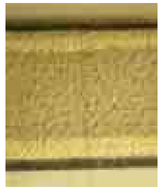
  - ☺ Benefits of both classes
  - ☺ Triggering of nonlinearity/bistability by mutual interactions among converters and magnet(s)

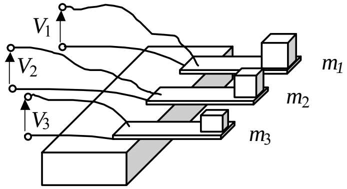
Contents

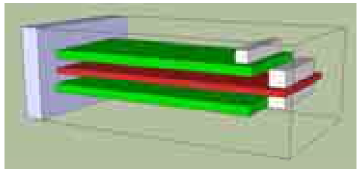
- Introduction
- Multi-frequency piezoelectric harvester arrays
- Nonlinear piezoelectric harvesters
- Conclusions

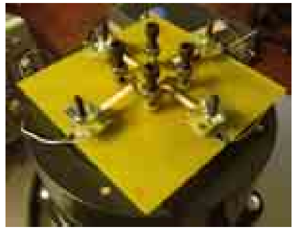
Conclusions

- Piezoelectric elements and PZT thick films on different substrates investigated for energy harvesting
- Promising approaches studied for energy harvesting from broadband vibrations:
  - Multi-Frequency converter arrays
  - Nonlinear converters
  - Nonlinear converter arrays







Acknowledgments

- T. Zawada and M. Guizzetti at MEGGIT-Ferroperm (DK): collaboration on the piezoelectric materials.
- P. Colombi at CSMT - Brescia for providing sputtering.
- MIUR:
  - Projects PRIN 20078ZCC92 (2008-2010); PRIN 2009KFLWJA (2011-2013).