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Enhanced electromechanical coupling of piezoelectric beams through an innovative design

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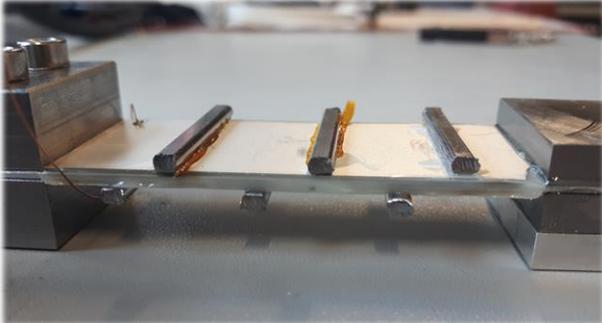
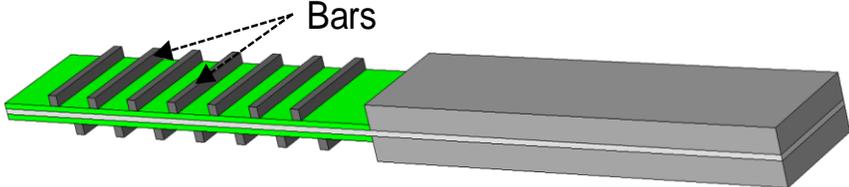
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D. Gibus, L. Tourtelier-Gallo, P. Gasnier, A. Morel, O. Freychet, A. Badel

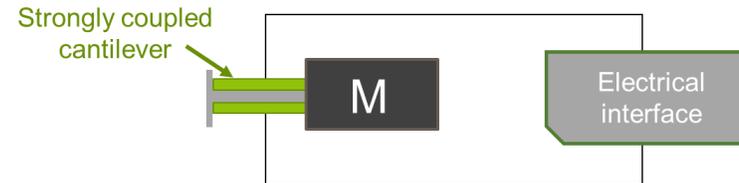
SYMME, Université Savoie Mont-Blanc

CEA Leti

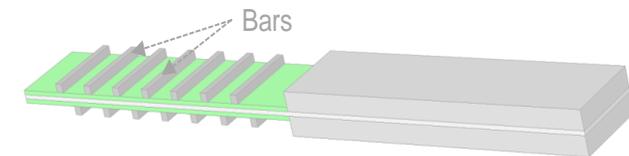
Enhanced electromechanical coupling of piezoelectric beams through an innovative design



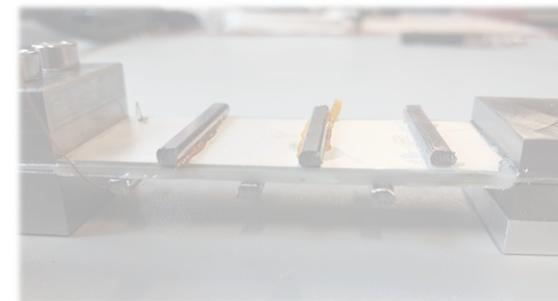
1. Context



2. Solution and simulations

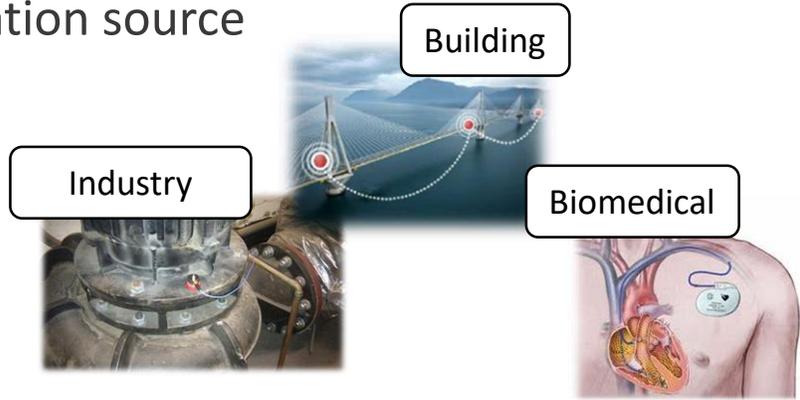


3. Experimental validation

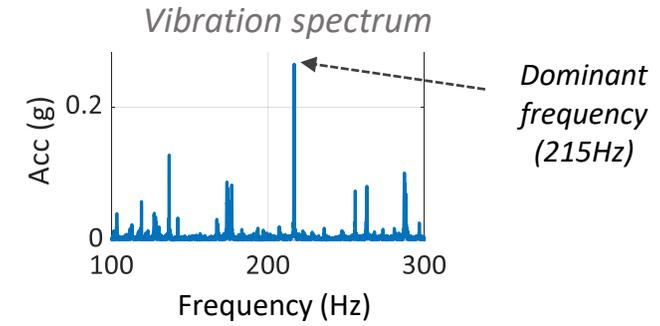


Vibration energy harvesting

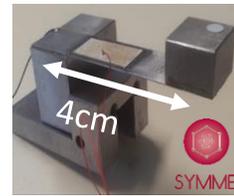
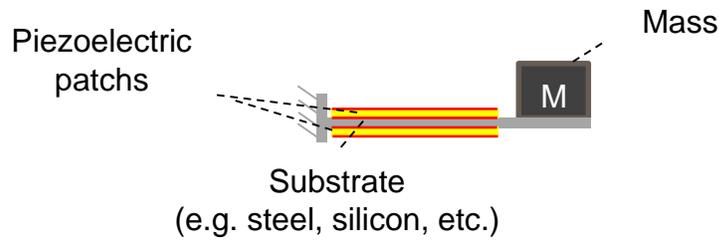
▪ Vibration source



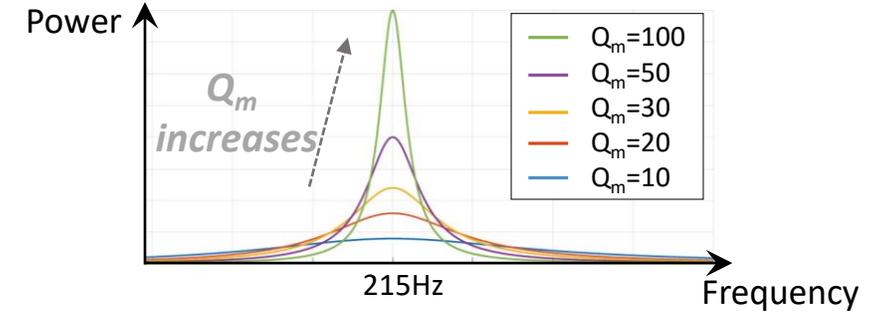
[EH Network Data Repository]



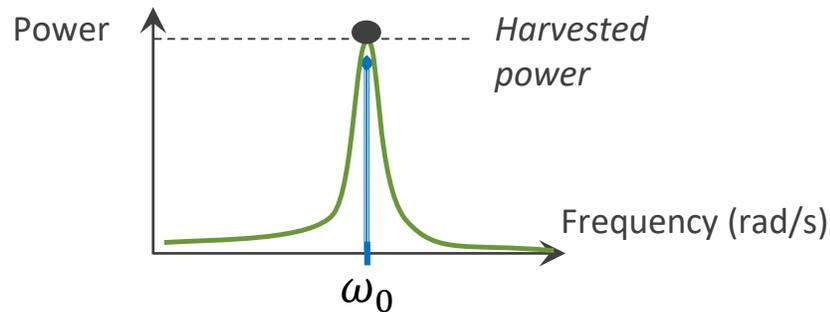
▪ Resonant structure



Power for various mechanical quality factors Q_m



▪ Tuning of frequencies



$$P_{\max} = \frac{M\gamma_M^2 Q_m}{8\omega_0}$$

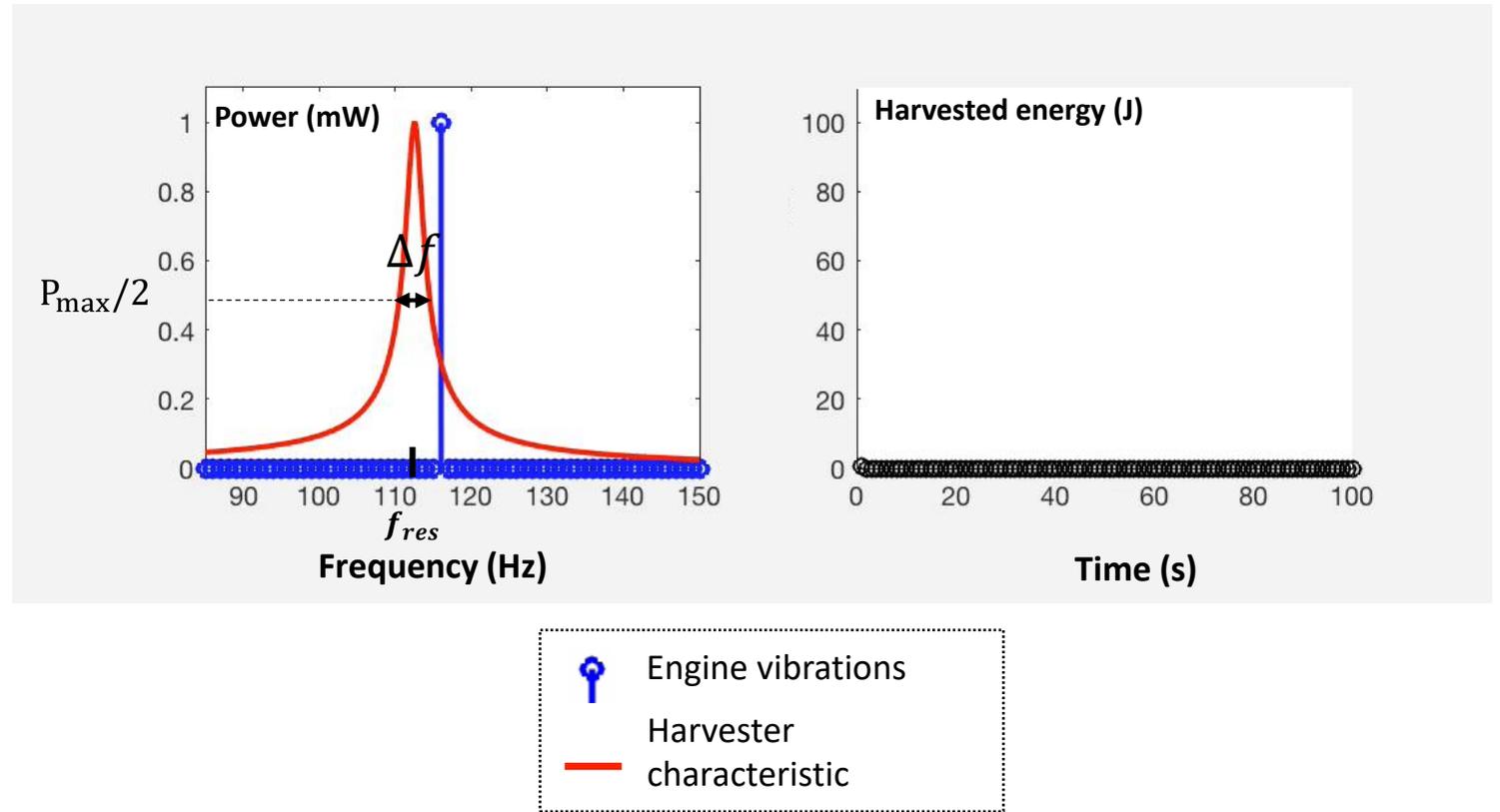
$$\text{Normalized Power Density} = \frac{P_{\max}}{\text{Volume} \times \gamma_M^2}$$

γ_M : Acceleration amplitude
 Q_m : Mechanical quality factor

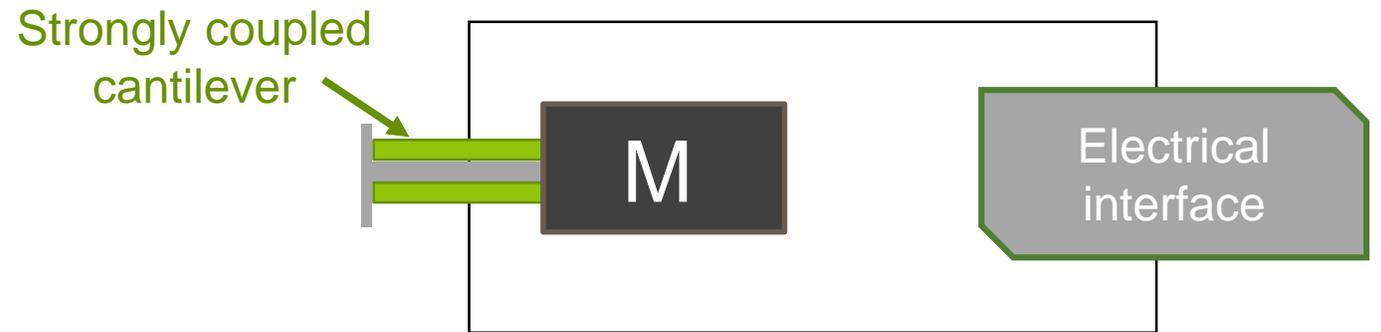
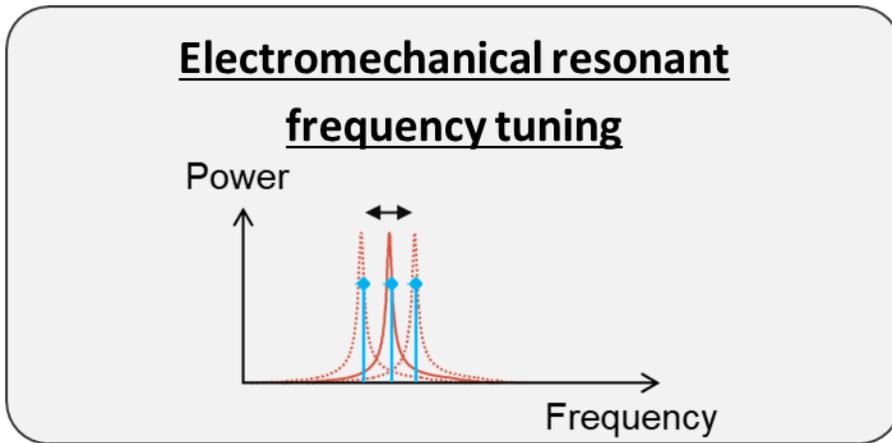
Enough power in small volume
 Usually 10-1 000 $\mu\text{W}/\text{cm}^3/\text{g}^2$

- Linear harvesters efficiencies drastically decrease if their resonant frequency do not match the vibration's frequency
- The intrinsic resonant frequency of piezoelectric energy harvesters may also varies with time, due to aging.

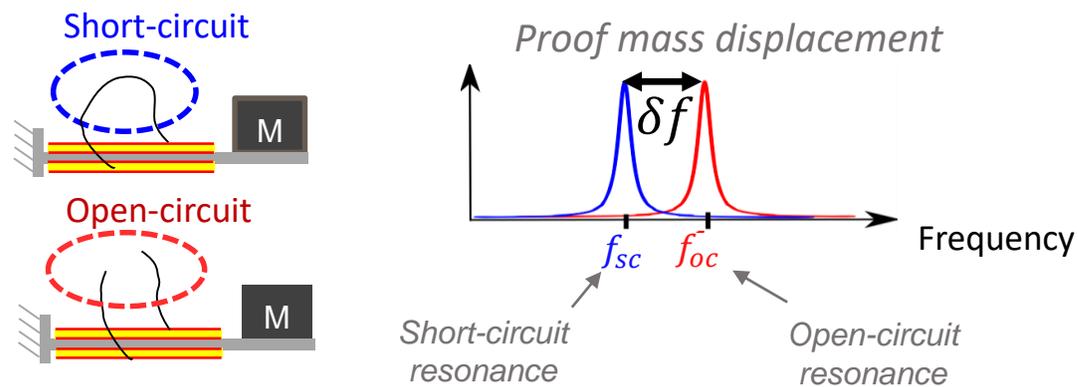
Δf : Frequency bandwidth



Necessity to either enlarge the harvesting bandwidth, or tune the harvester's resonant frequency



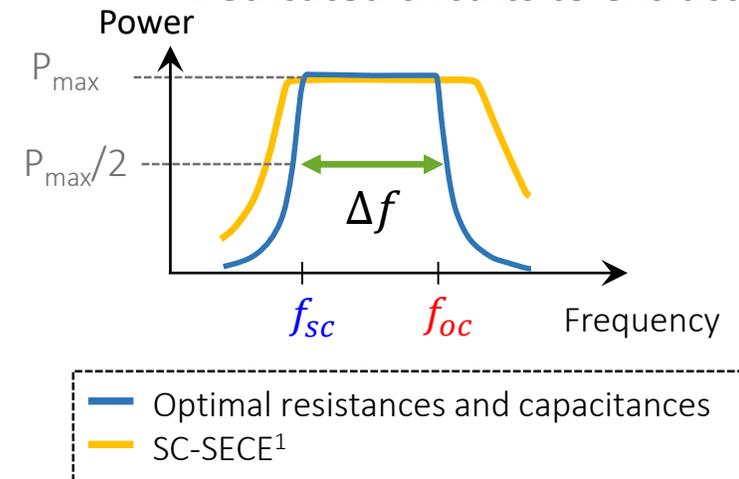
Electromechanical coupling coefficient k^2



$$k^2 = \frac{f_{oc}^2 - f_{sc}^2}{f_{oc}^2} = F(\text{materials, geometry})$$

→ Increasing the coupling k^2 increases the frequency bandwidth Δf

Dedicated circuits to extract power



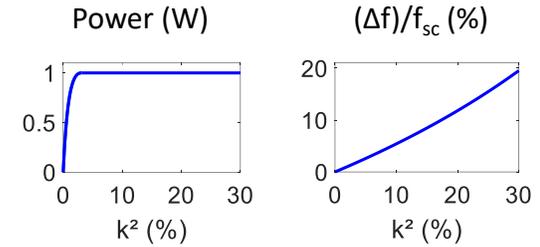
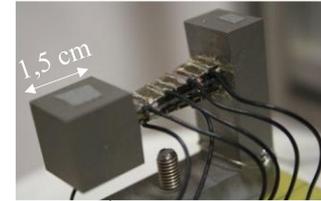
¹ A. Morel *et al.*, SMS, 2018

Electromechanical coupling coefficient

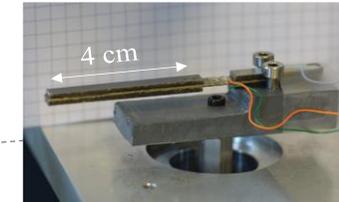
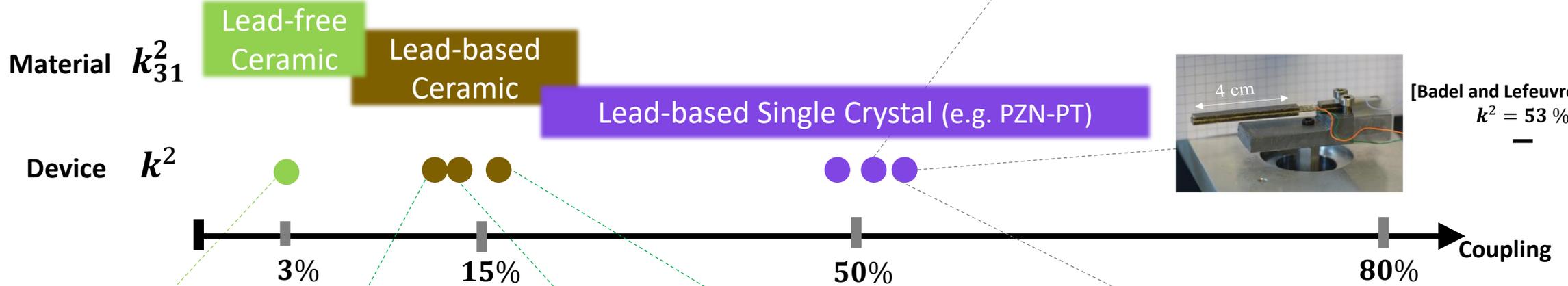
System coupling k^2 can be increased thanks to:

- The **piezoelectric material**
 - High electromechanical properties k_{31}^2
- Device **optimization**
 - Elastic energy localization in piezoelectric material
 - Strain distribution homogenization

[Ahmed-Seddik et al., 2012]
 $k^2 = 49\%$ ◀



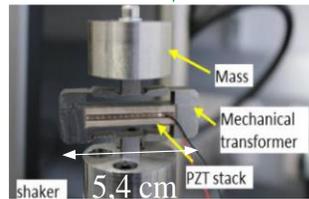
Commonly searched value : $k^2 = 2-3\%$.



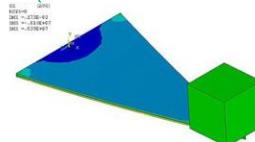
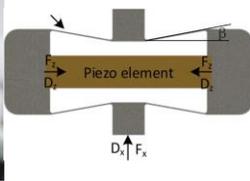
[Badel and Lefeuvre, 2014]
 $k^2 = 53\%$



[Clementi et al., 2021]
 $k^2 = 2.8\%$



[Kuang et al., 2020]
 $k^2 = 11\%$



[Siddiqui et al., 2016]
 $k^2 = 12\%$



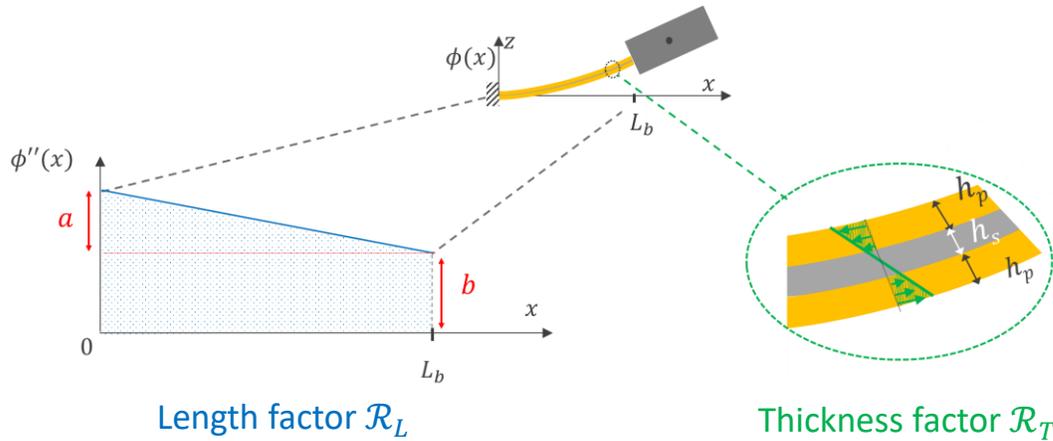
[Gibus et al., 2020]
 $k^2 = 16\%$



[Gibus et al., 2021]
 $k^2 = 50\%$

- ▲ Width tapered
- ▶ Thickness tapered
- Long proof mass
- ◊ Flexensional

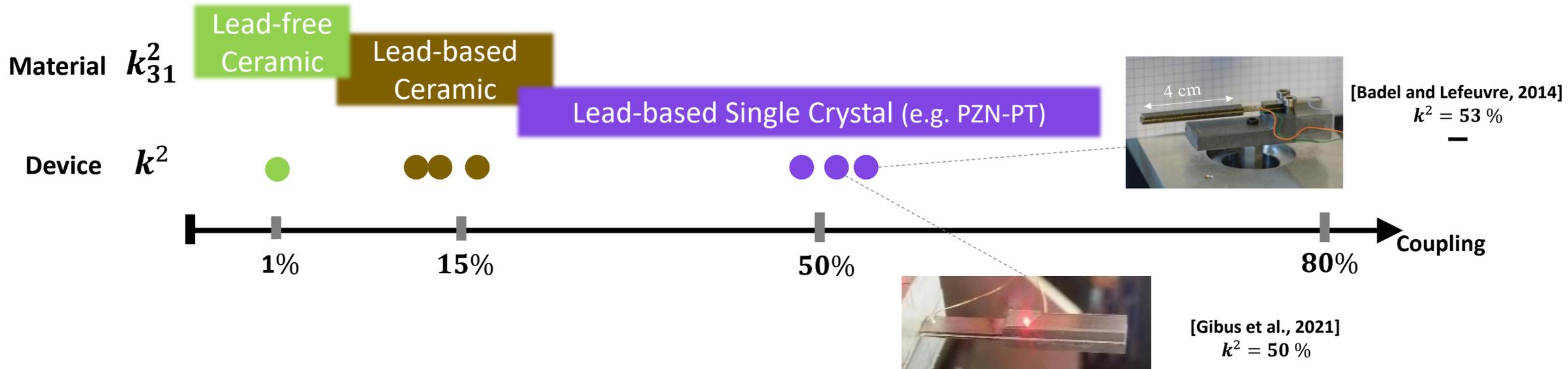
Cantilever optimization



Long proof mass useful to increase coupling coefficient as the strain becomes uniform

Material thicknesses should be optimized

Gibus et al., Applied Energy 2020

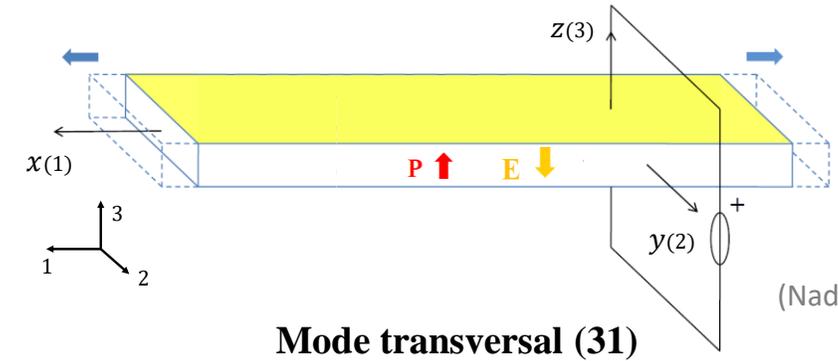


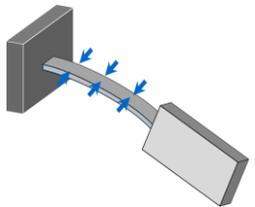
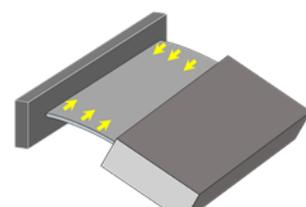
Material coupling

$$\begin{pmatrix} S \\ D \end{pmatrix} = \begin{bmatrix} s^E & -d^t \\ d & \epsilon^T \end{bmatrix} \begin{pmatrix} T \\ E \end{pmatrix}$$

d : Piezoelectric matrix
 s^E : Suppliance matrix
 ϵ^T : Permittivity matrix

T : Stress vector
 S : Strain vector
 D : Displacement electric field vector
 E : Electric field vector

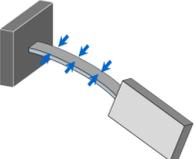
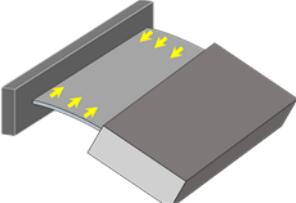


Narrow beam	Wide beam
 <p>Only lateral strain →</p> <p>No lateral stress : $T_2 = 0$</p> $k_{31}^2 = \frac{d_{31}^2}{\epsilon_{33}^T s_{11}^E}$ <p>(Commonly used coupling)</p>	 <p>Only lateral stress →</p> <p>No lateral strain : $S_2 = 0$</p> $k_{31}^{w2} = \frac{\left(d_{31} - \frac{s_{12}^E}{s_{22}^E} d_{32} \right)^2}{\left(\epsilon_{33}^T - \frac{d_{32}^2}{s_{22}^E} \right) \left(s_{11}^E - \frac{s_{12}^E{}^2}{s_{22}^E} \right)}$

For ceramics, $k_{31}^{w2} = \frac{k_{31}^{l2} (1 + \nu_p)}{1 - k_{31}^{l2} \nu_p}$ with the Poisson ratio ν_p defined as $\nu_p = -\frac{s_{12}^E}{s_{11}^E}$

$$k_{31}^{w2} > k_{31}^2$$

Take benefit of material parameters

	Narrow beam	Wide beam
Assumption	 <p>Only lateral strain →</p>	 <p>Only lateral stress →</p>
Ceramic PZT-5A	$k_{31}^l{}^2 = 15.1\%$	$k_{31}^w{}^2 = 34.2\%$

Experimentally validated
 $k^2 = 11.3\%$



Width × 5
 $k^2 \times 160\%$

$k^2 = 16.4\%$



Gibus et al., Applied Energy 2020

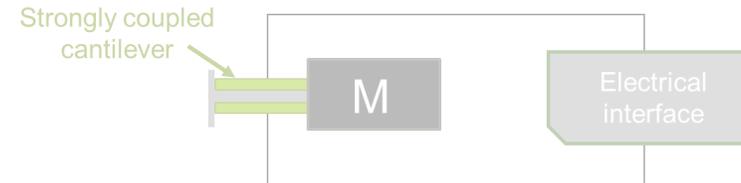
Beam width should be at least **twice** bigger than the **length** for piezoelectric ceramics

but

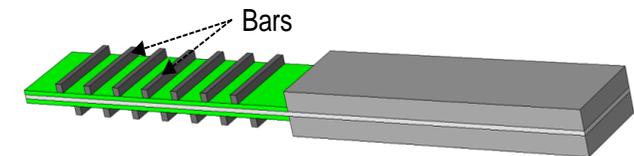
As ↗ beam length helps to ↘ resonant frequency, design issues can occur for small devices volumes and with low resonant frequencies

Is it possible to reach with this behavior without enlarging the beam ?

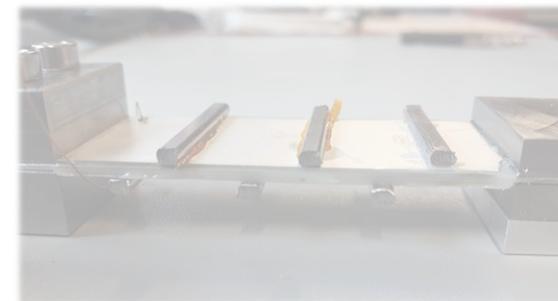
1. Context



2. Solution and simulations

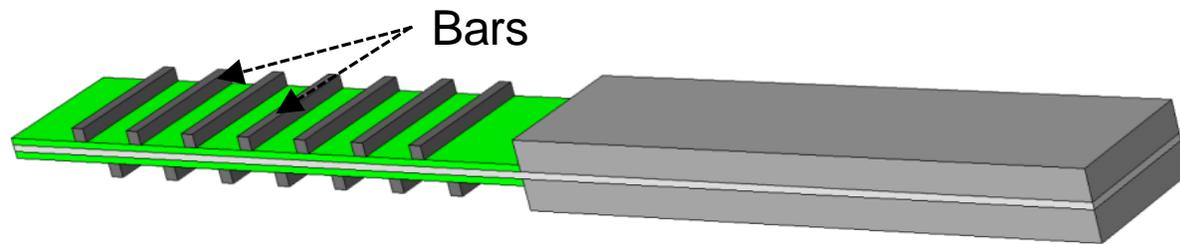
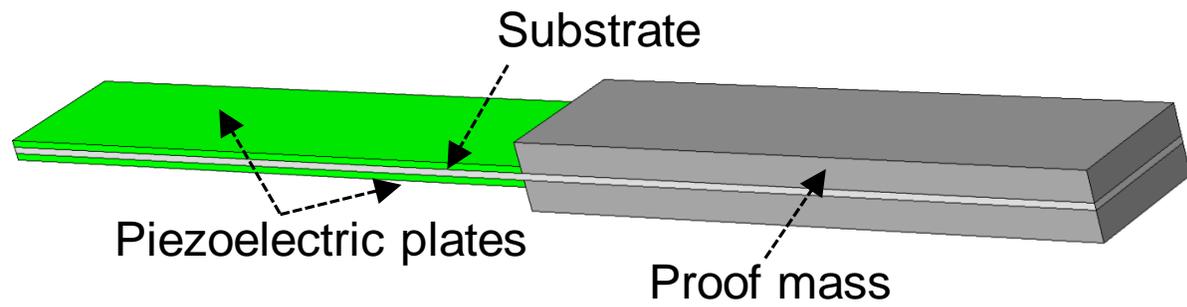


3. Experimental validation

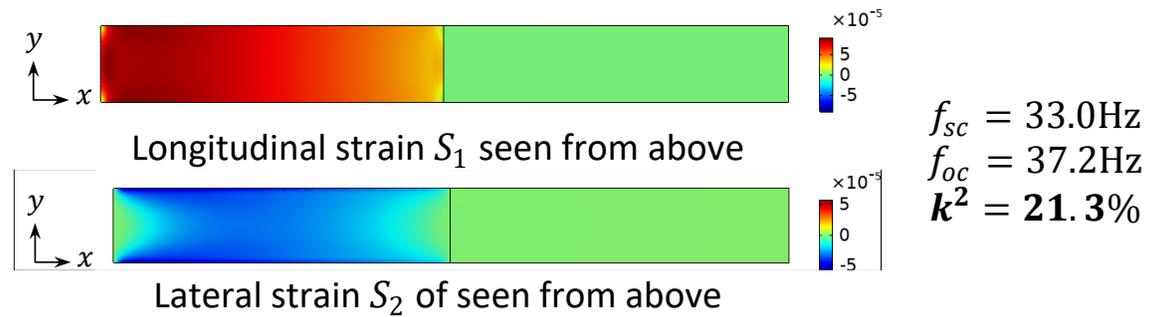


Proposal : adding lateral bars to reduce lateral strain for narrow beams

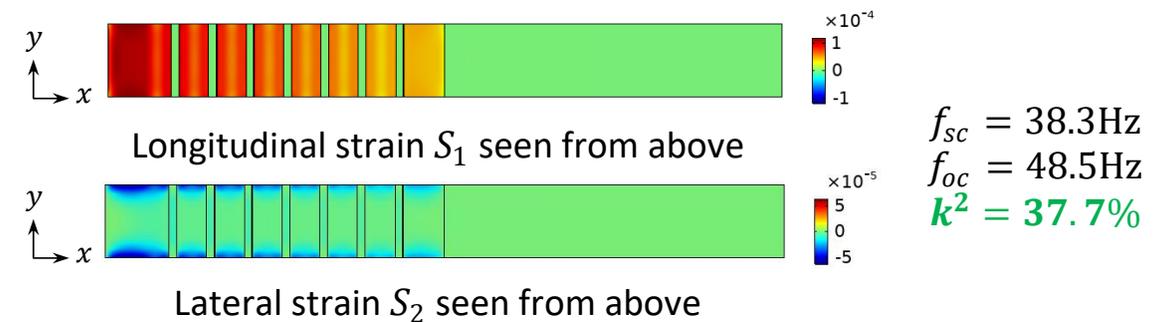
Example with PMN-PT Material on Comsol (FEM)

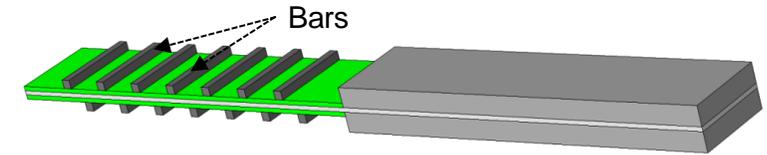


Without bars



With bars





The improvement of the coupling depends on

- **The initial cantilever**

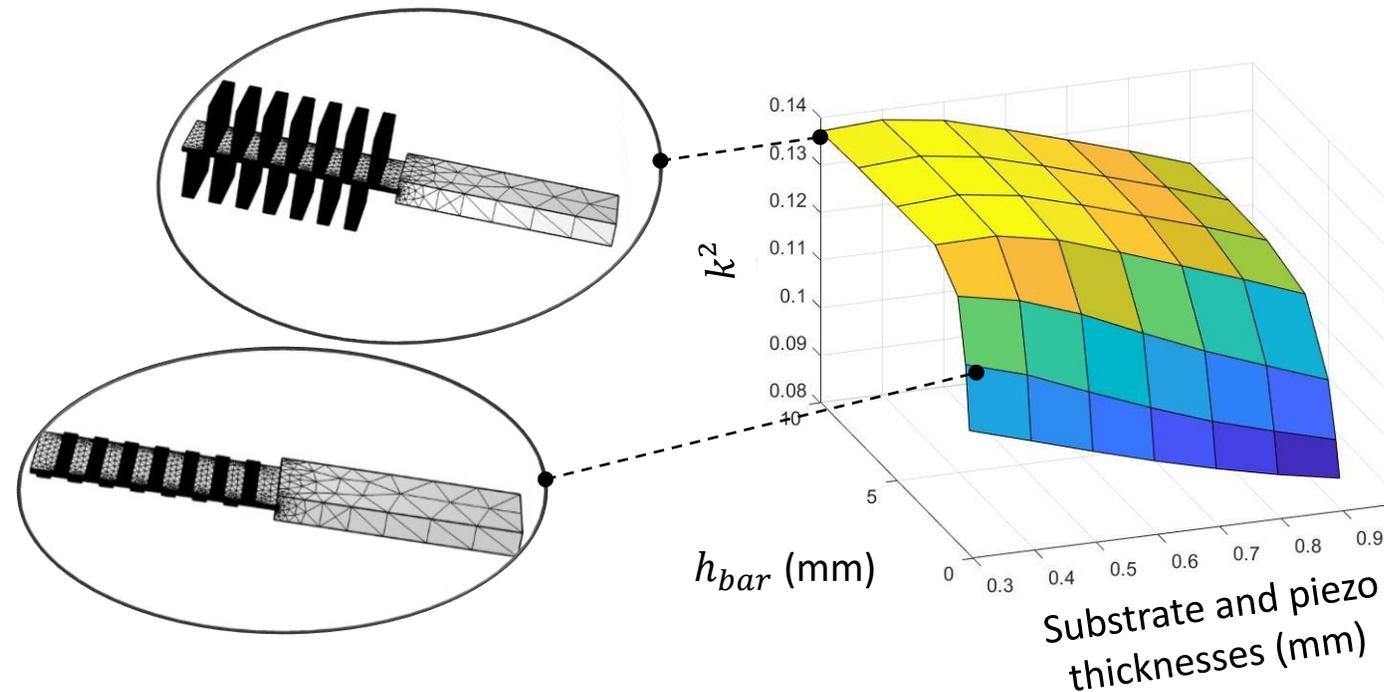
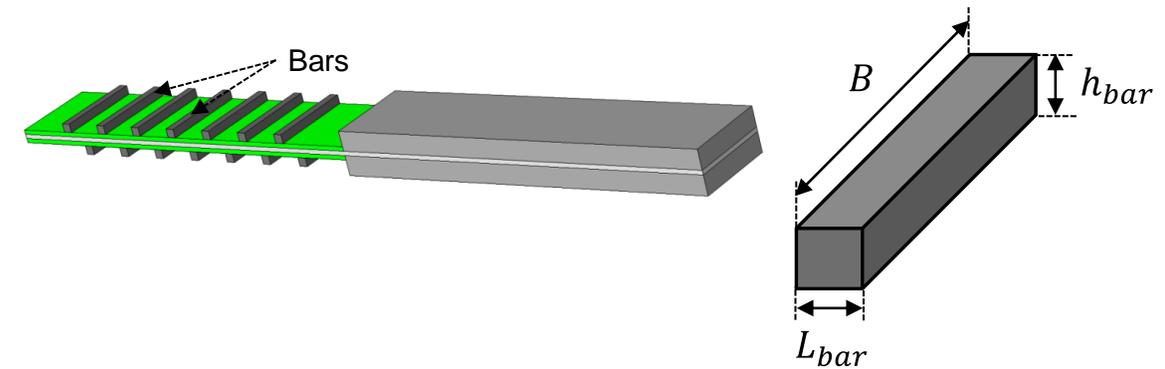
- Coupling coefficients k_{31}^l and k_{31}^w of the piezoelectric material,
- The stiffness of the piezoelectric material and the substrate
- The geometry (length of the beam, mass and thickness of the piezoelectric materials and the substrate)

- **The bars**

- Dimensions (height h_{bar} , length L_{bar})
- The stiffness of the material of the bars
- Number and arrangement (distance between each bar, staggered or face to face arrangement)

Parametric study

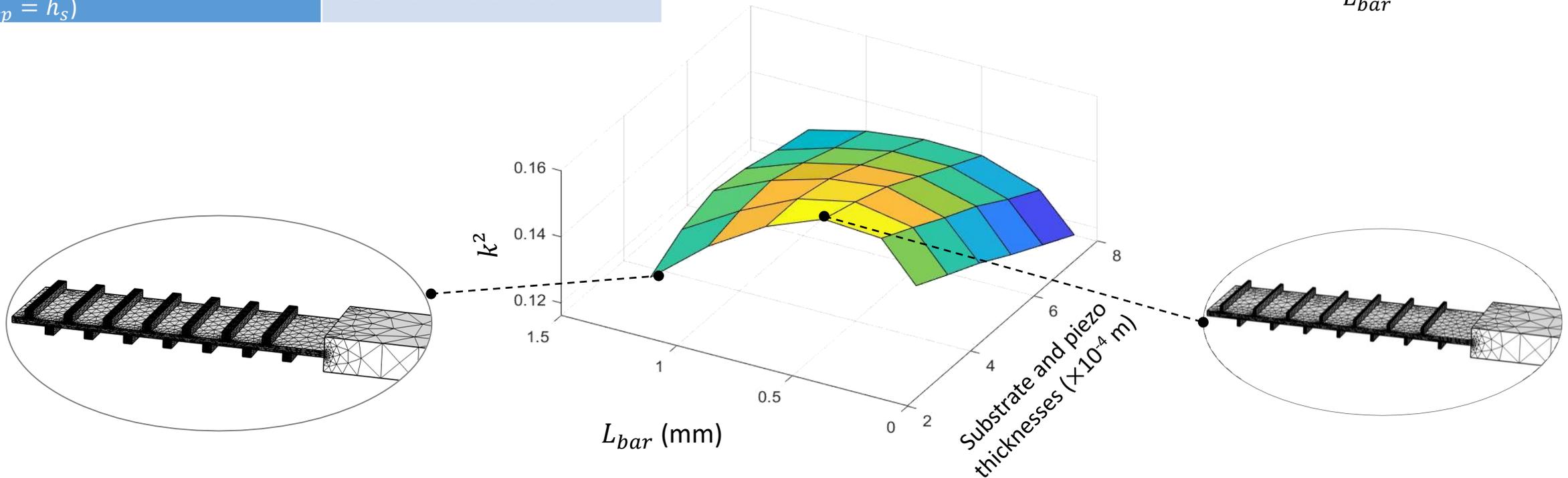
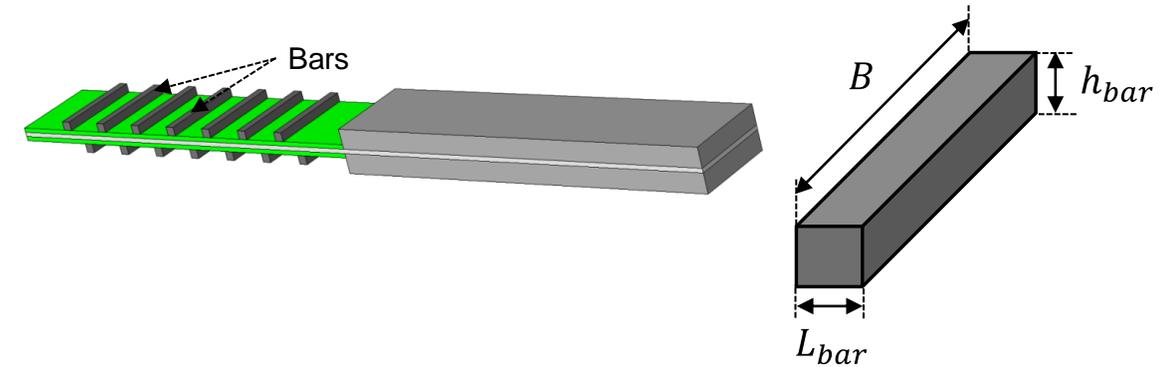
Fixed parameters	Values
Materials	PZT 4 and steel
Beam width	15 mm
Bar width L_{bar}	1 mm
Beam length	45 mm
Variable parameters	
Bar thickness h_{bar}	0.25-0.5-1-2.5-5-7.5-10 mm
Substrate and piezo thicknesses ($h_p = h_s$)	0.3-0.4-0.5-0.6-0.7-0.8-0.9mm



h_{bar} could be maximized and a plateau is reached

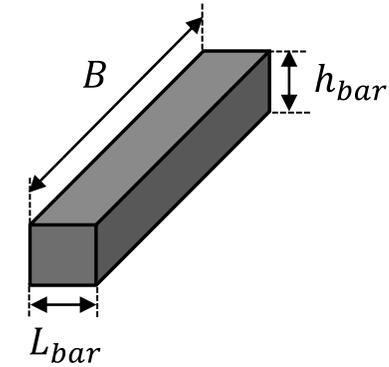
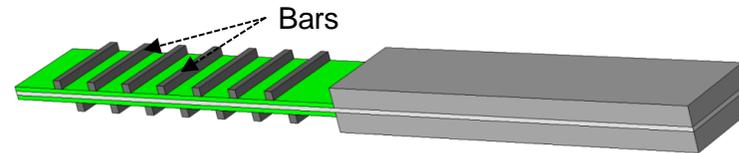
Parametric study

Fixed parameters	Values
Materials	PZT 4 and steel
Beam width	15 mm
Bar thickness h_{bar}	$4 \times$ substrate thickness h_s
Beam length	45 mm
Variable parameters	
Bar width L_{bar}	0.1-0.25-0.5-0.75-1-1.25 mm
Substrate and piezo thicknesses ($h_p = h_s$)	0.3-0.4-0.5-0.6-0.7-0.8 mm



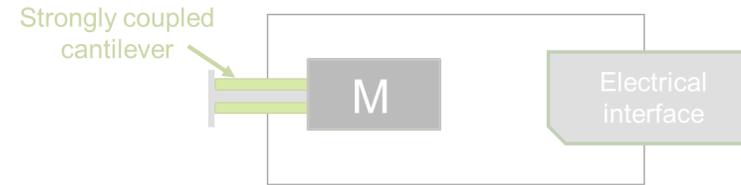
An optimal value of L_{bar} exists

According to our first studies, the bars should cover around 8 % of the beam length

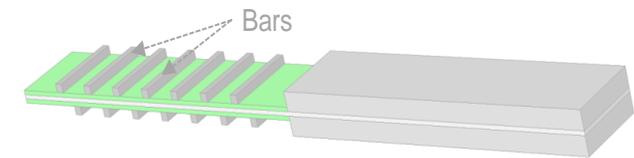


Parameters	Optimal configuration
Bar thickness h_{bar}	At least $4 \times$ substrate thickness (h_s)
Bar width L_{bar}	Around 8 % of the beam length
Number of bars	At least 3 one each side. No significant tendency with more bars
Arrangement (staggered of face to face)	No significant tendency

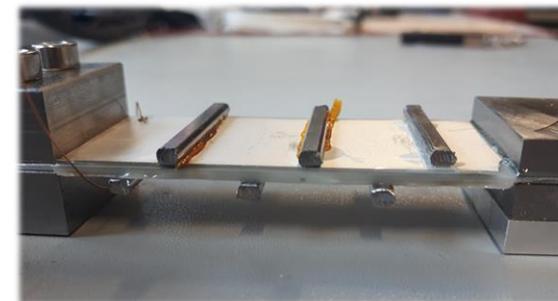
1. Context



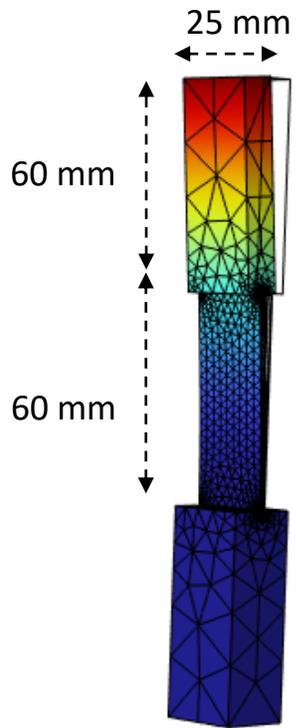
2. Solution and simulations



3. Experimental validation



Prototype



$$f_{sc} = 26.6 \text{ Hz}$$

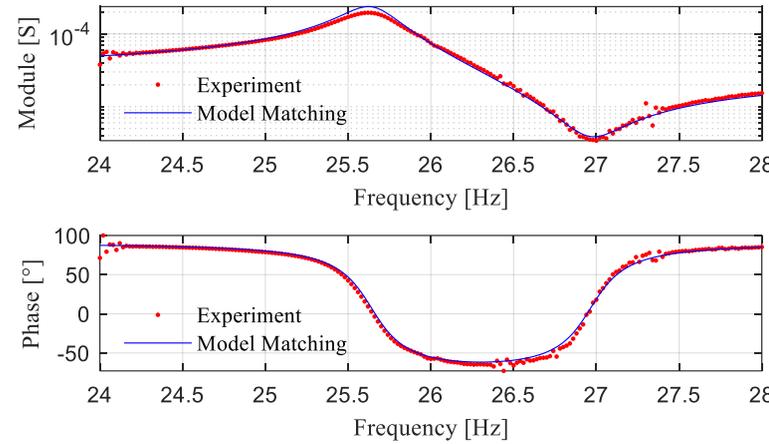
$$k^2 = 10.5 \%^*$$

$$f_{sc} = 25.6 \text{ Hz}$$

$$k^2 = 9.5 \%$$

* Considered glue thickness of 100 μm between the piezoelectric plates and the substrate, and considered distance of the piezoelectric plates from clamp of 500 μm

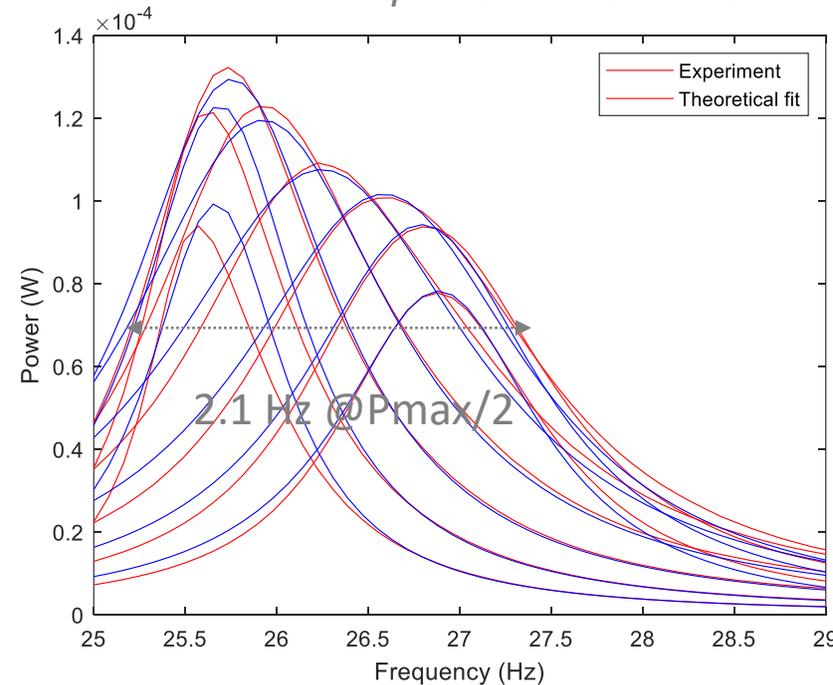
Measure admittance and fit



Bimorph :

- 1 mm thick aluminum substrate
- 2 \times 0.5 mm thick PZT 5H plates
- 10 mm thick steel proof mass

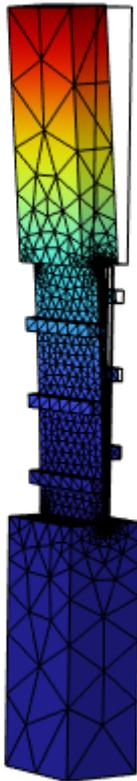
Measured mean power on resistive loads and fit



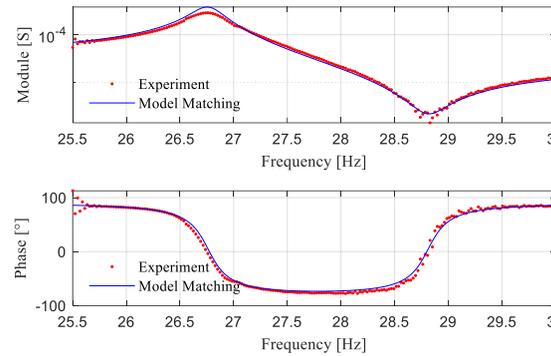
$P_{max} = 130 \mu\text{W} @ 0.2 \text{ m/s}^2$

8.5 % bandwidth at $P_{max}/2$

Results

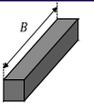


Measure admittance and fit

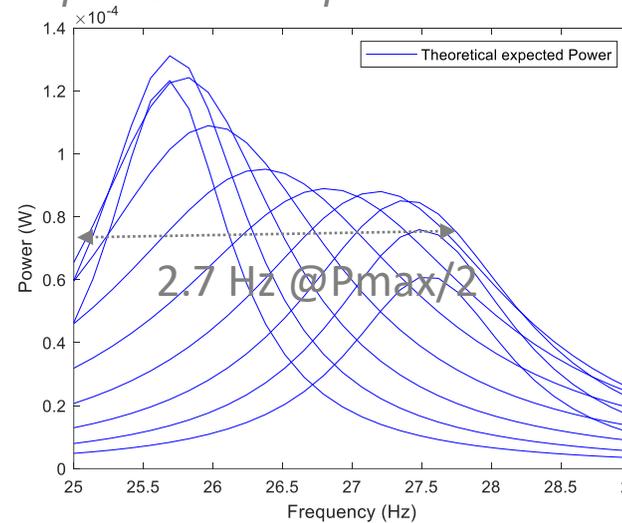


6 Bars:

- 2 mm x 3 mm steel bars
- 3 on each side
- staggered arrangement



Expected mean power on resistive loads



$P_{max} = 130 \mu W @ 0.2 \text{ m/s}^2$

10.5 % bandwidth at $P_{max}/2$

k^2 is multiplied by 1.42 with the bars (from 9.5 % to 13.7%)

The bandwidth is expected to be multiplied by 1.23

$$f_{SC} = 28.2 \text{ Hz}$$

$$k^2 = 14.3 \%^*$$

$$f_{SC} = 26.7 \text{ Hz}$$

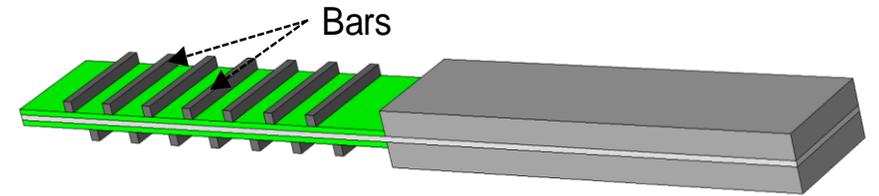
$$k^2 = 13.7 \%$$

* Considered glue thickness of 100 μm between the bars and the piezoelectric plates

Conclusion

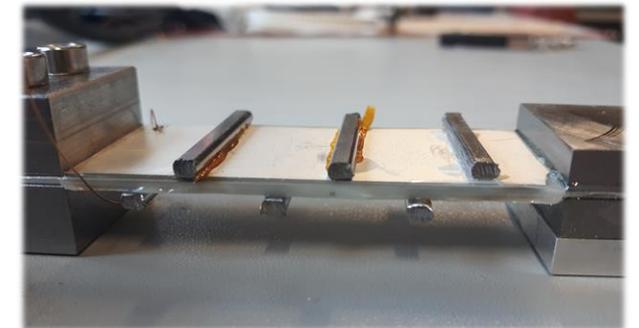
An innovative design was presented for maximizing the coupling

- to maximize the power
- to maximize the frequency bandwidth



Experimental validation was made with PZT 5H

- $\times 1.42$ on the electromechanical coupling coefficient k^2
- $\times 1.24$ expected on the frequency bandwidth



Prospects

- Deeper analysis of the materials impact
- Validation with lead free materials

ΕΥΧΑΡΙΣΤΩ

(Thank you)

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SYMME

