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Materials, Devices and Applications

Linear motors based on piezoelectric MEMS

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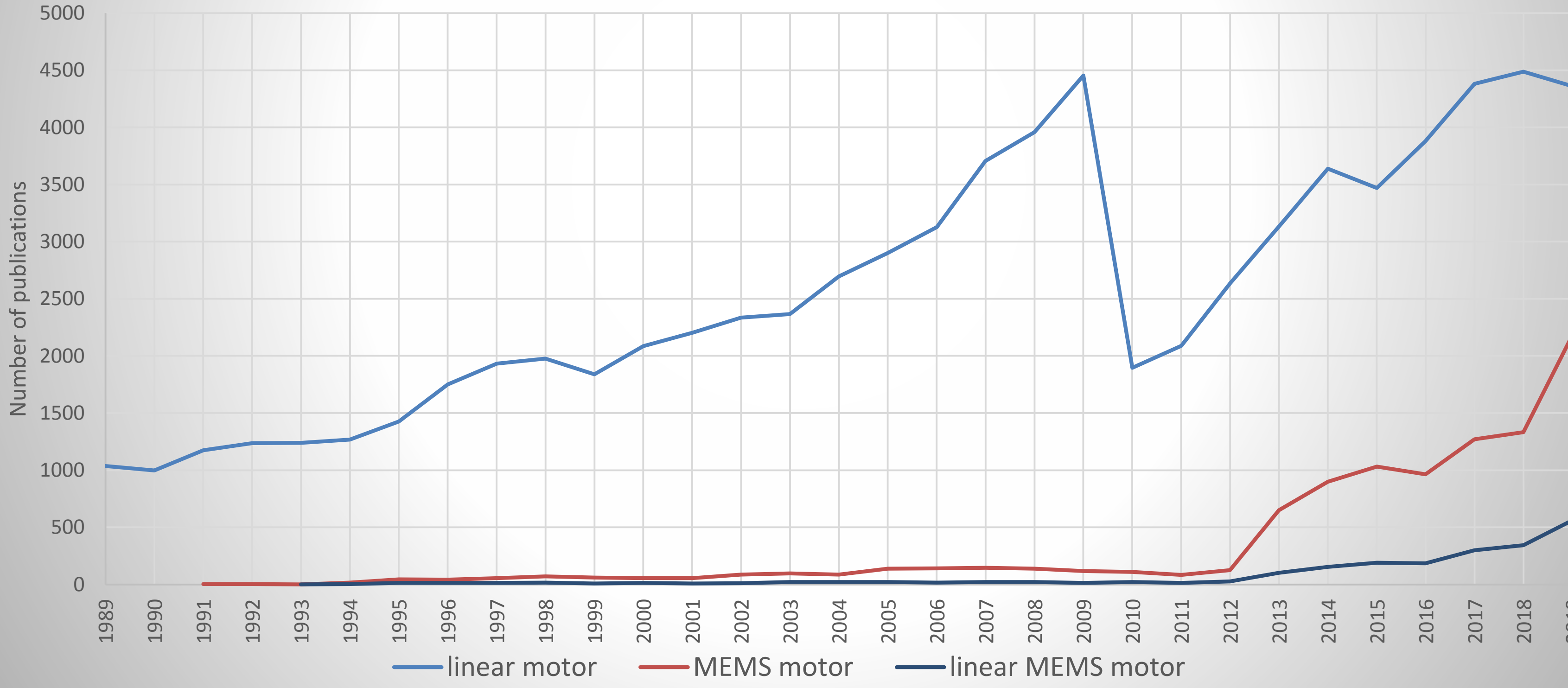
Outline

- Introduction
- Design and modelling
  - Travelling-wave based
  - Standing-wave based
- Materials and methods
- Results
- Conclusions

Introduction

Motivation

Increasing interest in miniaturised **MEMS**-based **linear motors**



Source: Web of Science™

Introduction

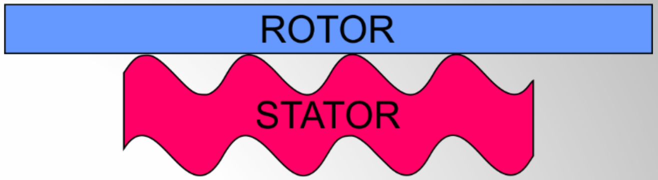
Application requirements for linear motors

- Large displacement
- High output force
- Energy efficiency
- High speed
- High positional precision

Miniaturisation benefits

- Improved performance
- Compact size
- Low power consumption
- Low manufacturing costs
- Array configuration

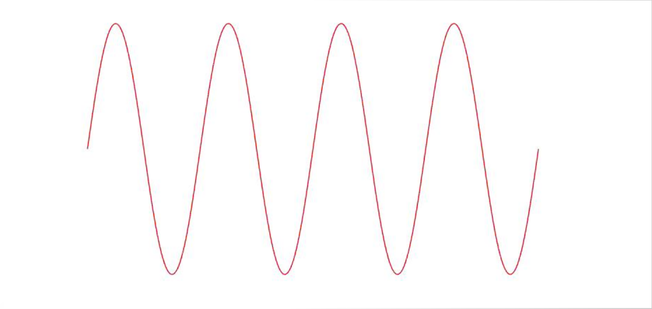
Ultrasonic motors



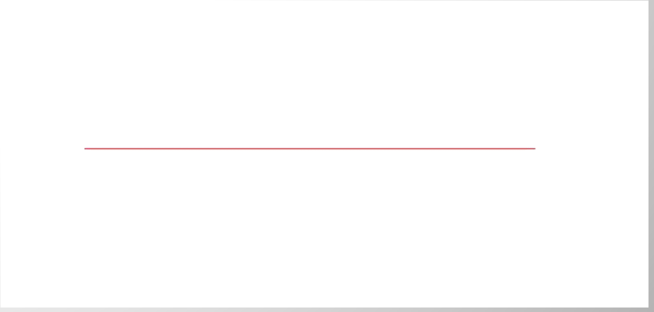
Classification

- Elastic vibration nature
  - Travelling-wave (TW)
  - Standing-wave (SW)
- Axis of movement
  - Rotational
  - Linear
- Directionality
  - Unidirectional
  - Bidirectional

TW



SW



MEMS-based motors

- Electro-thermal actuation
- Pressure-driven
- *Piezoelectric actuation*
    - All-electrical scheme
    - High efficiency
    - High output forces
    - Scaling down to the micrometric size

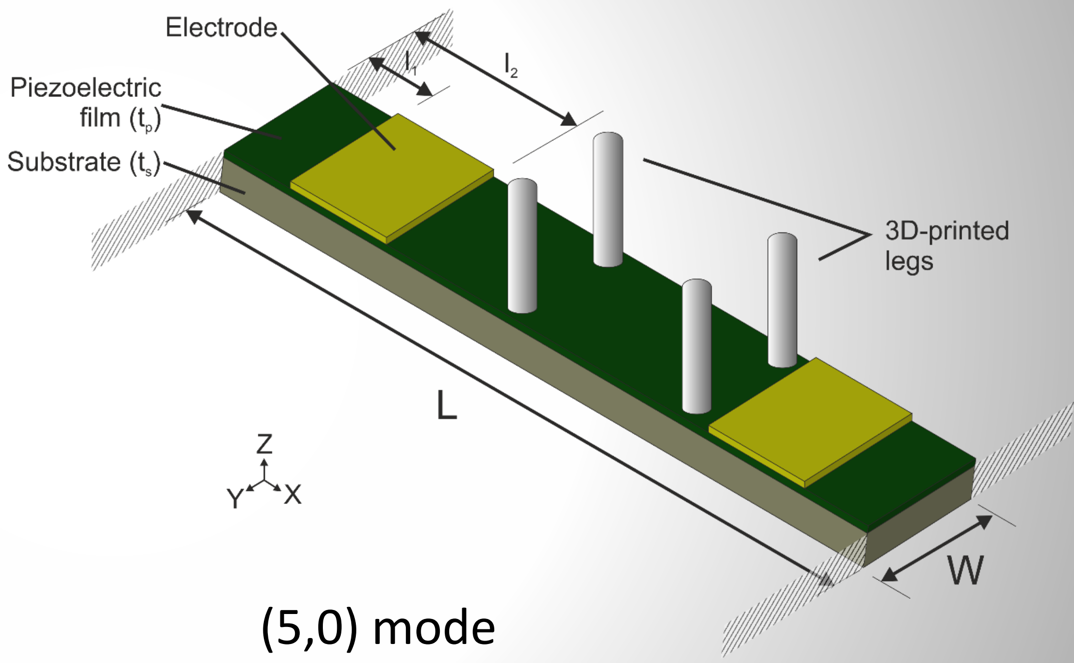
Design and modelling

Our work: MEMS (Silicon+AlN) + 3D printed legs

Description of the motor

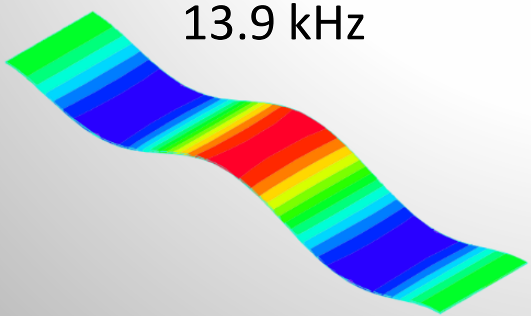
Bridges

- Length = 10 mm
- Width = 2 mm
- Substrate thickness = 30 µm
- Piezoelectric thickness = 1 µm

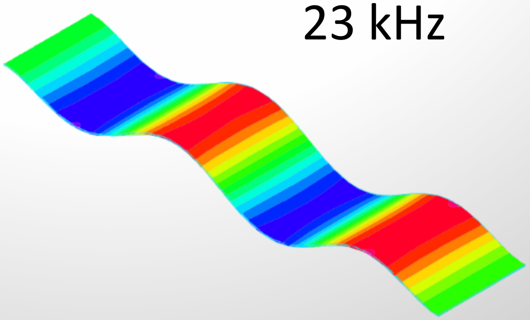


Flexural modes

(4,0) mode
13.9 kHz



(5,0) mode
23 kHz



Travelling-wave actuation

Introduction

Ideal TW:

Not possible in finite structures due to B.C.

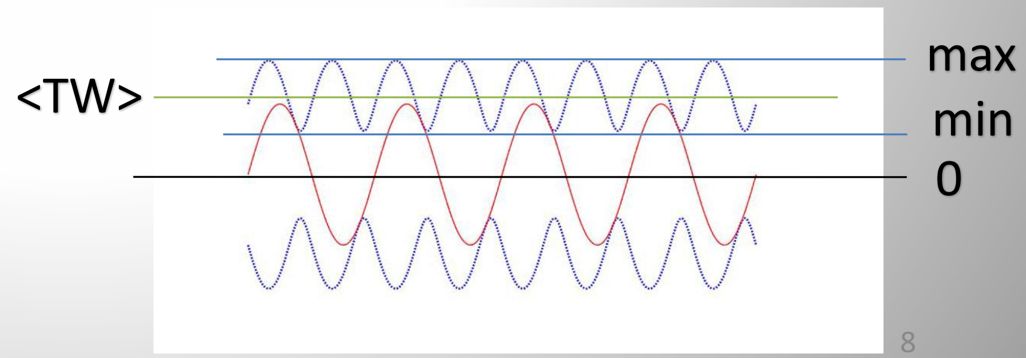
$$w(x,t) = A\sin(kx - \omega t) = A\left(\sin(kx)\cos(\omega t) - \sin\left(kx + \frac{\pi}{2}\right)\cos\left(\omega t + \frac{\pi}{2}\right)\right)$$

Mode superposition (1D) of two contiguous modes:

$$w(x,t) = [Q_s\Phi_s(x) + Q_A\Phi_A(x)]\cos(\omega t) + [Q_s\Phi_s(x) - Q_A\Phi_A(x)]\cos(\omega t + \varphi)$$

- Driving frequency (ω) → mid-frequency between resonances
- Spatial quadrature → Symmetric (Φ_s) + Antisymmetric (Φ_A) modes
- Temporal shift (φ)→ 90° phase shift

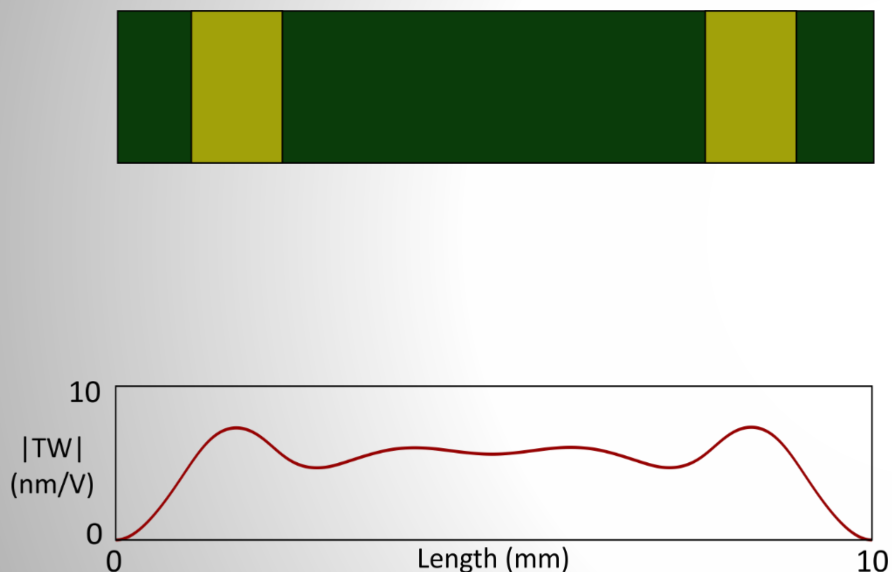
- Optimisation of contributions Q_s and Q_A with patch geometry:
  - Minimum SWR=max/min
  - Maximum <TW>=Avg.(envelope)



Travelling-wave actuation

Electrode optimisation

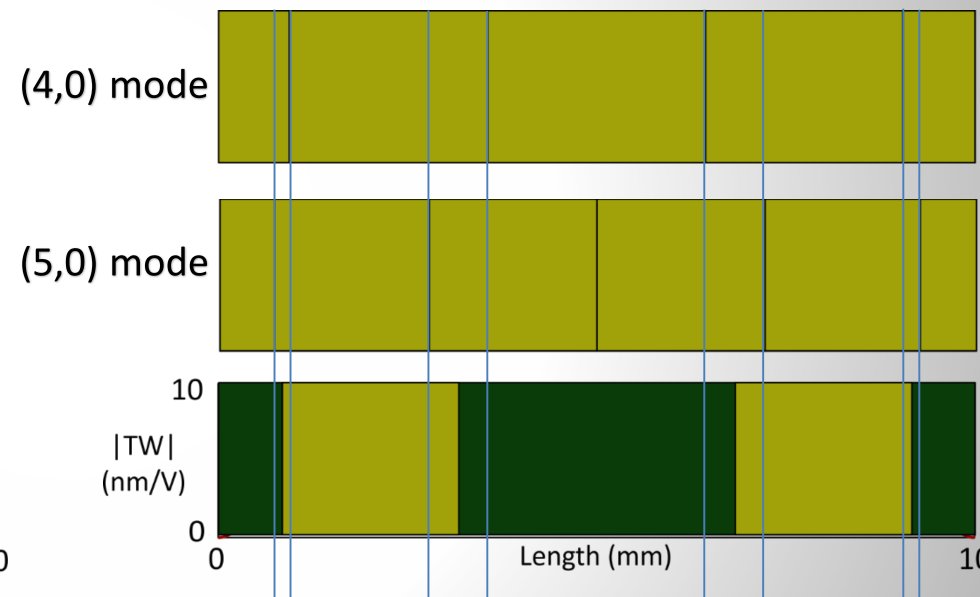
TW-optimised patch



SWR=1.3
<TW> = 5.7 nm/V

Minimum SWR

Zeros-based patch[1]



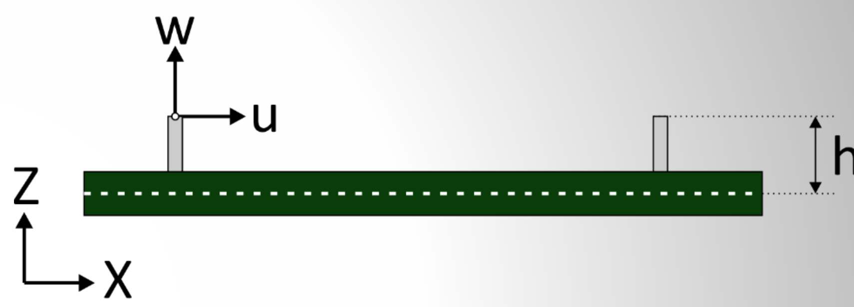
SWR=1.52
<TW> = 8.05 nm/V

Maximum <TW>

[1] Ruiz-Díez, V. et al. Bidirectional Linear Motion by Travelling Waves on Legged Piezoelectric Microfabricated Plates. *Micromachines* **2020, 11,5.**

Travelling-wave actuation

Leg placement



Vertical displacement:

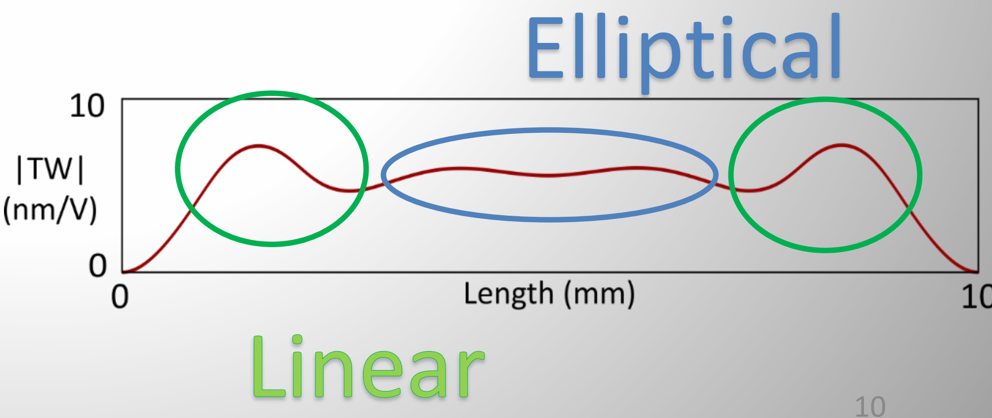
$$w(x,t) = A(x)\cos\left(\omega_f t + \theta(x)\right)$$

Horizontal displacement:

$$u(x,t) = -h\frac{dw}{dx} = -h\left(A'(x)\cos\left(\omega_f t + \theta(x)\right)\right) + h\left(A(x)\theta'(x)\sin\left(\omega_f t + \theta(x)\right)\right)$$

For elliptical trajectory:

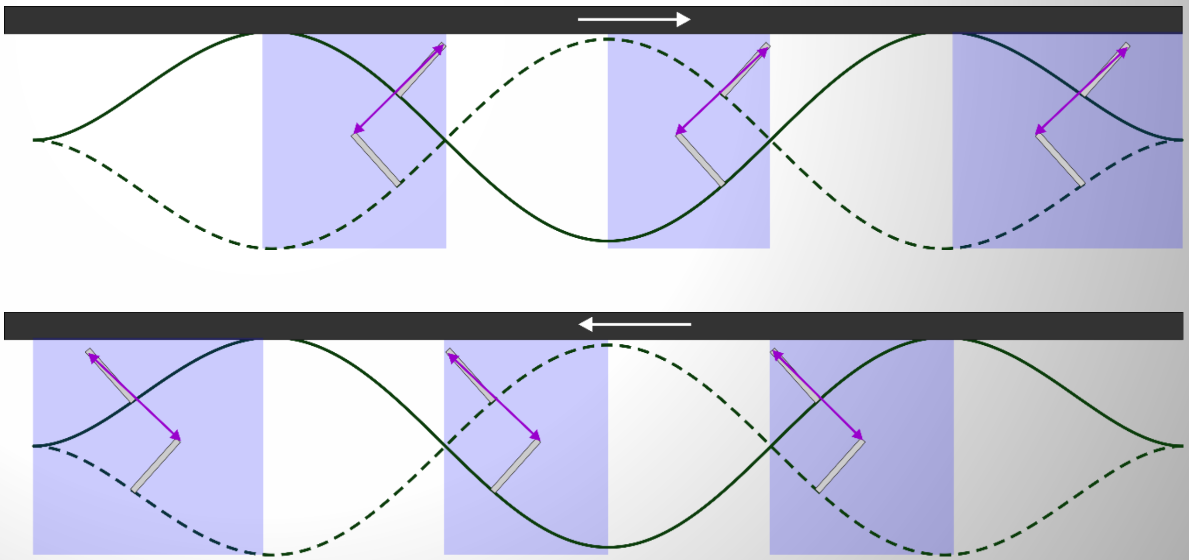
$A'(x) = 0$ → **Central plateau**



Standing-wave actuation

Introduction

- Linear trajectory of leg tip.
- High amplitude due to resonance.
- Bidirectionallity using two different modes (symmetric + antisymmetric)



Design and modelling

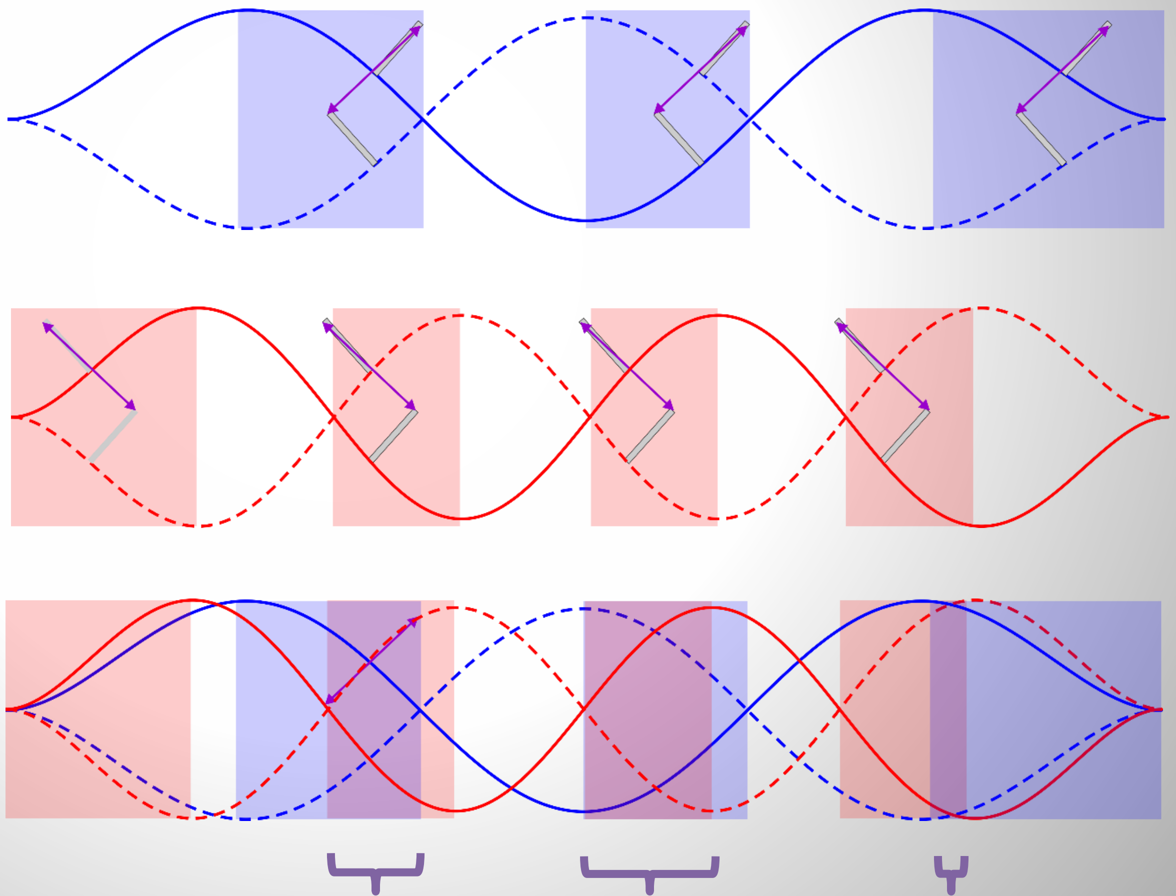
Standing-wave actuation

Leg position

(4,0) mode
Forward direction
Right region of crest

(5,0) mode
Backward direction
Left region of crest

Overlapped area
Direction depending on mode

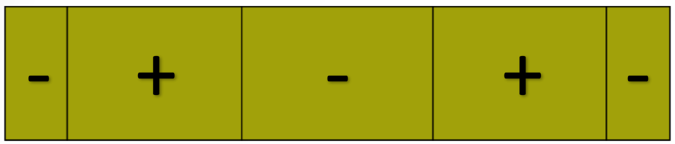


Standing-wave actuation

Electrode optimisation

Patch shape | **Phase optimisation**

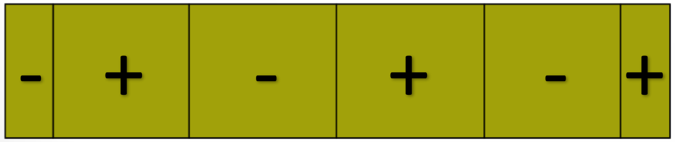
(4,0) mode



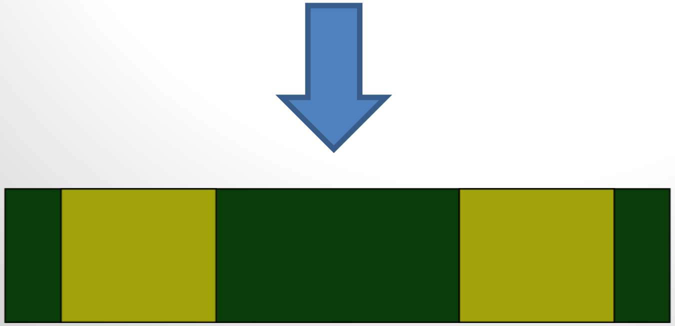
+: 0° phase difference
-: 180° phase difference

0° phase difference

(5,0) mode



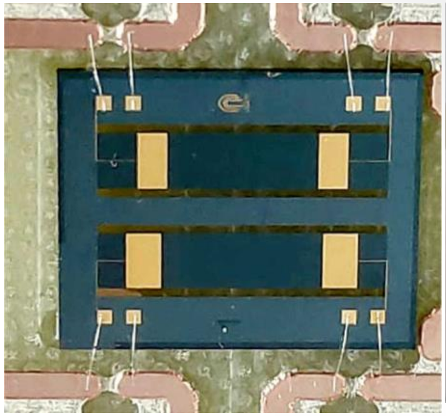
180° phase difference

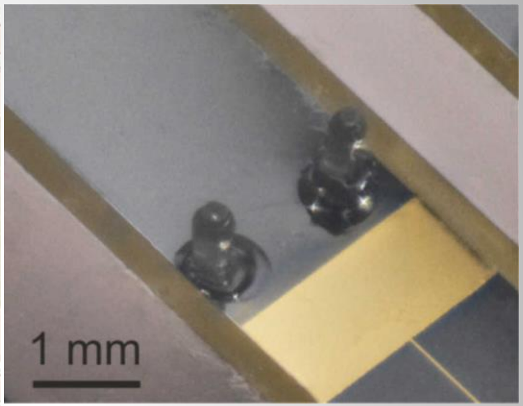


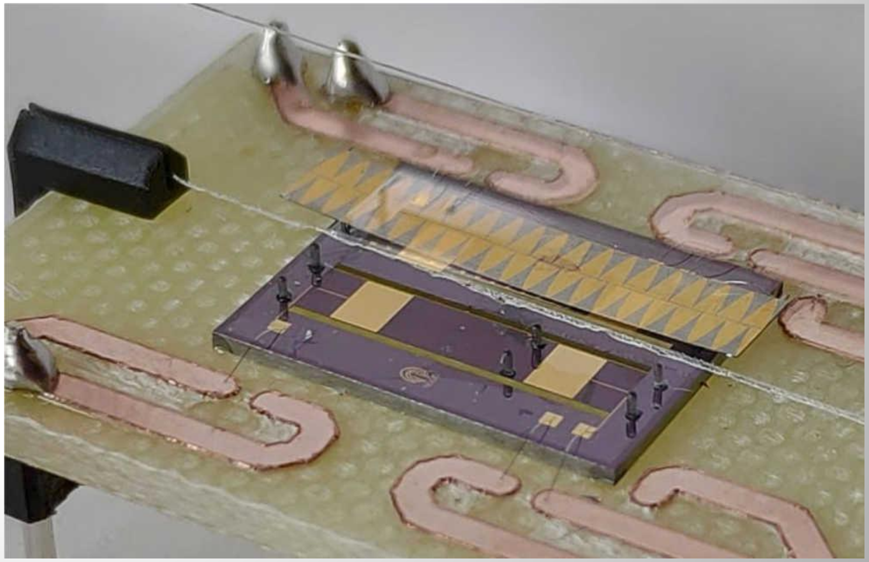
Fabrication

Bridges
- Length = 10 mm
- Width = 2 mm
- Substrate (Si) thickness = 30 µm
- Piezoelectric (AlN) thickness = 1 µm
- Metallisation (Au) thickness = 500 nm
- Patches:
    - [970 - 2200] mm
    - [7800 - 9030] mm

Legs
- Length = 750 µm
- Diameter = 300 µm
- Silicone-based resin
- Position = 3.2 mm
    - TW: central plateau
    - SW: bidirectional region
- Cyanoacrylate glue





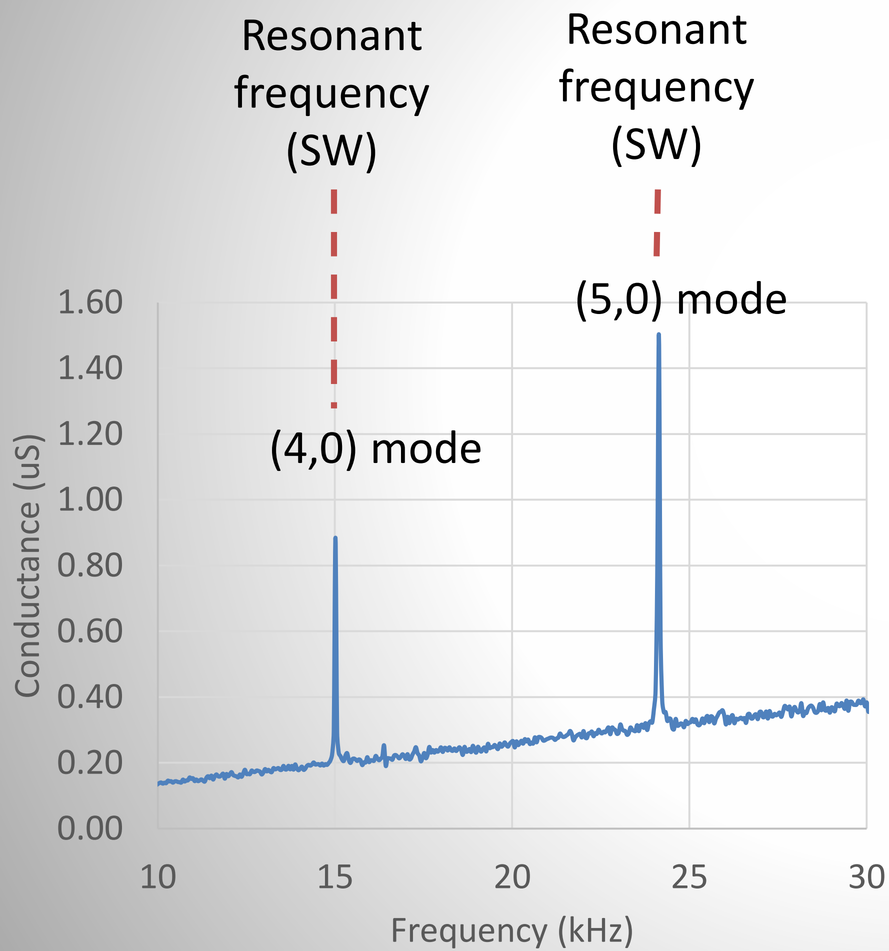


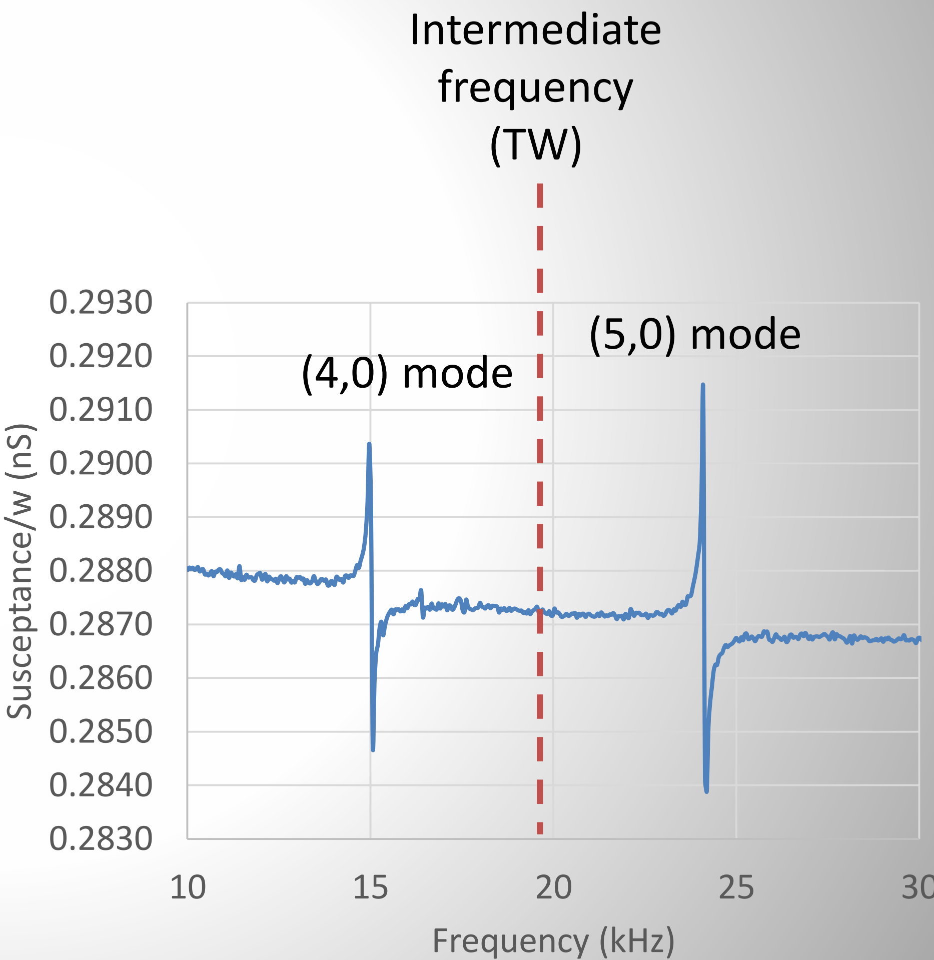
Materials and methods

Characterization

- Electrical impedance
  - Performance of the piezoelectric layer
  - Figures of merit: frequency, Q-factor, conductance
- Laser Doppler vibrometry
  - Mode identification
  - TW & SW characterization
- Kinetic
  - High FPS digital video camera (200 FPS, x100 objective)
  - Computer controlled AWG
  - Motion tracking software
  - 2mg, 15x3x0.02 mm silicon slider

Electrical impedance





Results

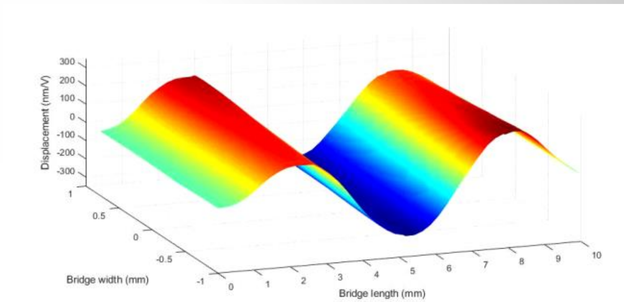
Optical characterization

SW (4,0) mode

15.25 kHz

0° phase difference

$\bar{w} \sim 320\ nm/V$

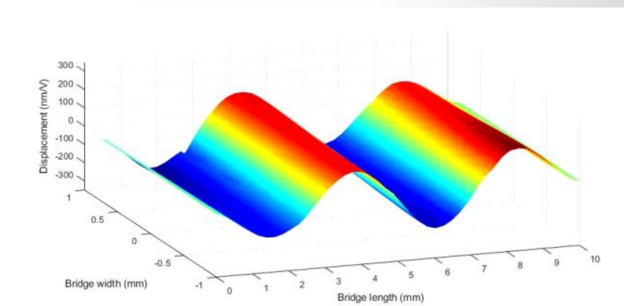


SW (5,0) mode

24 kHz

180° phase difference

$\bar{w} \sim 240\ nm/V$



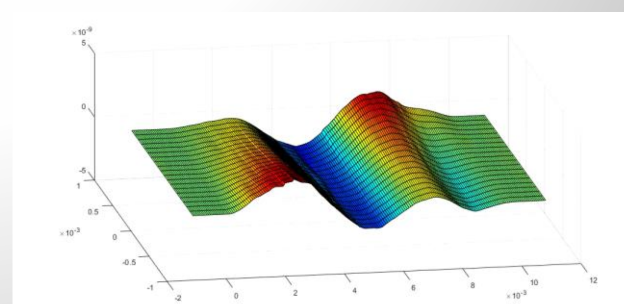
TW (4,0)&(5,0) mode

19.55 kHz

90° phase difference

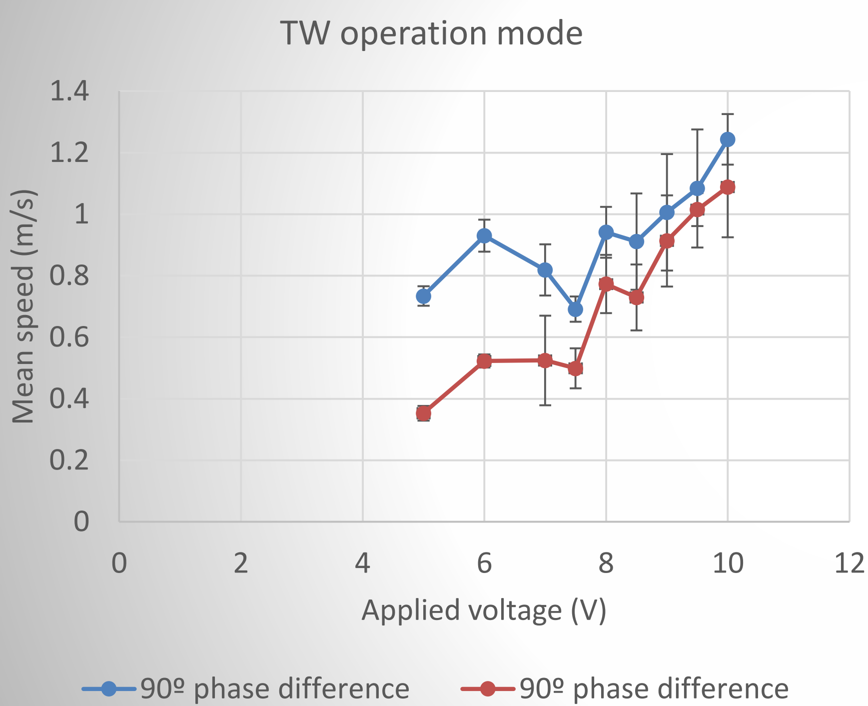
$< TW > = 4.76\ nm/V,$

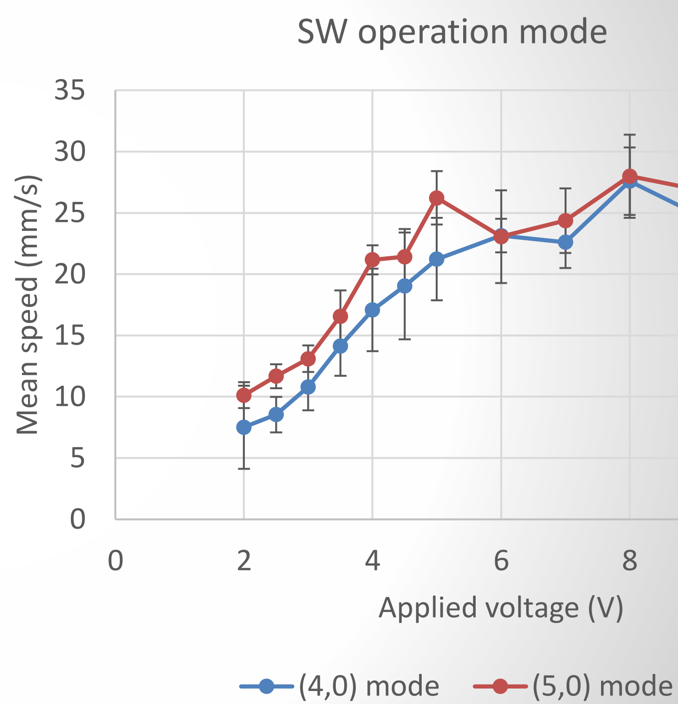
$SWR = 1.6$

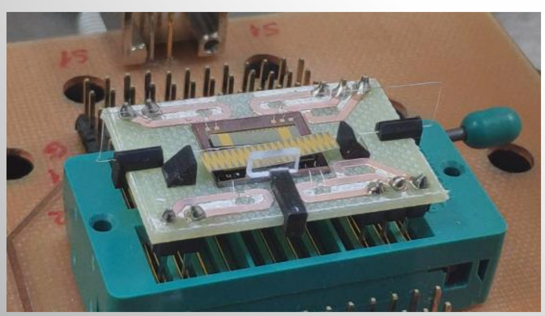


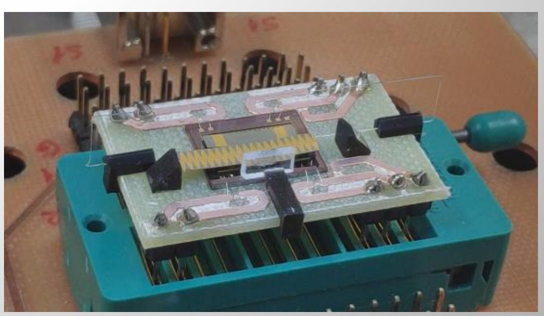
Kinetic characterization

Speed





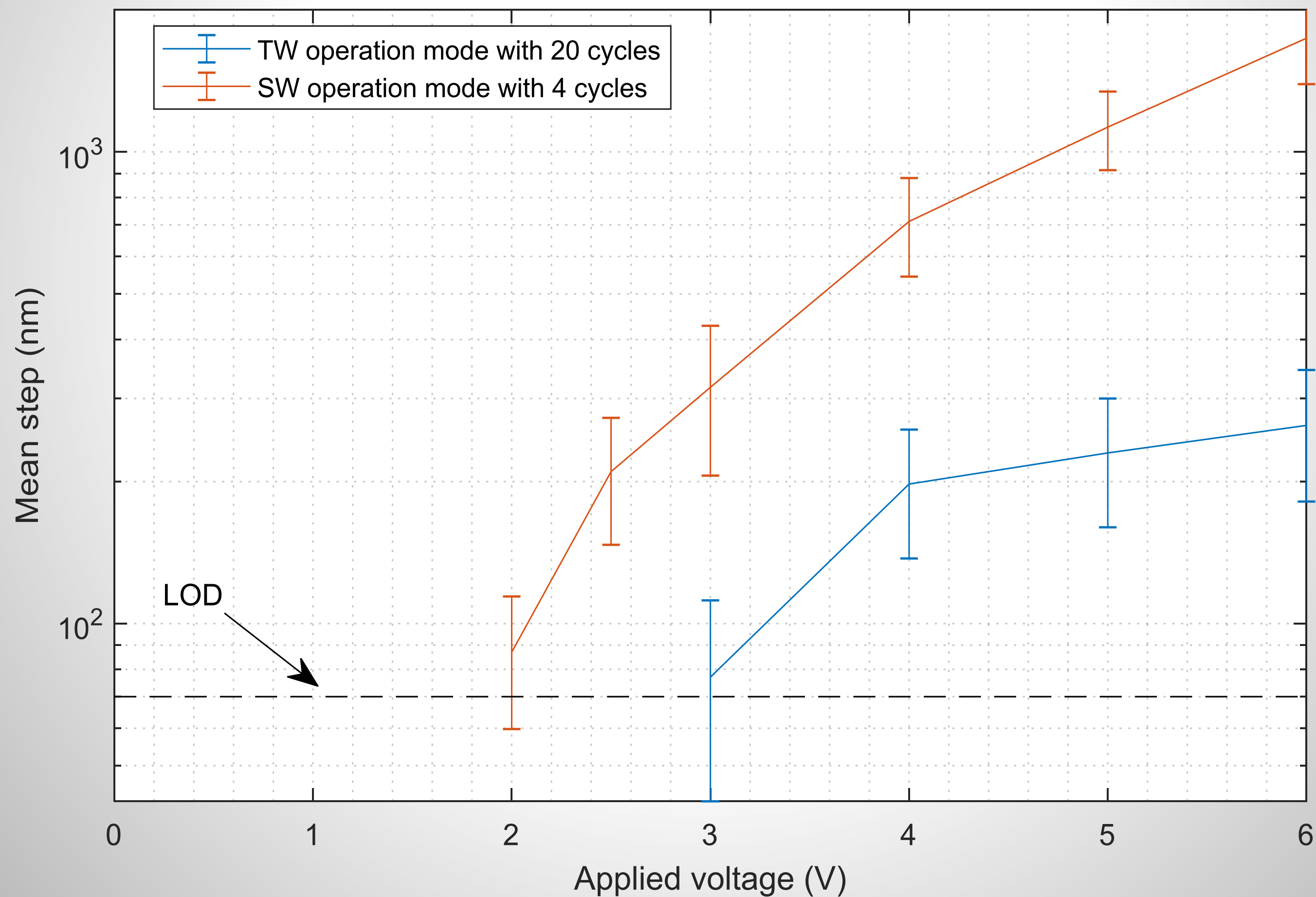




Results

Kinetic characterization

Nanopositioning



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Conclusions

- Design of efficient linear MEMS-based piezoelectric motors.
- Hybrid technology: MEMS resonator + 3D-printed legs
- Modelling and optimisation of the wave-driven stator:
  - Travelling-wave
  - Standing-wave
- Maximum conveyor speed at 10V with 2mg slider:
  - 1.2 mm/s in TW operation mode
  - 25 mm/s in SW operation mode
- Minimum step as low as 70 nm.

Thanks for your attention