Simulating Electrostatic Zipping Actuation in a Three-Chamber Peristaltic Micropump

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Introduction

Conventional electrostatic actuators notoriously suffer from significant drawbacks, including the need for large actuation voltages and a limited range of motion. Electrostatic zipping actuators, by contrast, have tailored structures with small local gaps which maintain high electrostatic forces and a induce a gradual "zipping" motion of a diaphragm, enabling significantly larger ranges of motion at lower applied voltages [1-3]. In this work, we exploit this concept to design and simulate an electrostatic zipping 3-chamber peristaltic micropump.

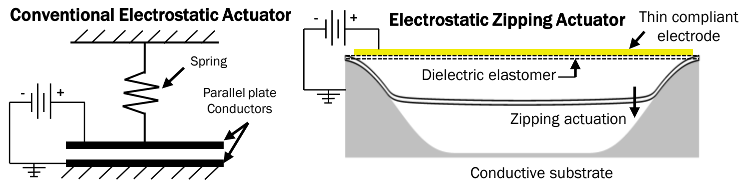


Fig. 1: Schematic diagram of a conventional parallel plate actuator (left) and an electrostatic zipping actuator (right); the small local gaps near the corners significantly facilitate actuation.

Electrostatic Zipping Micropump

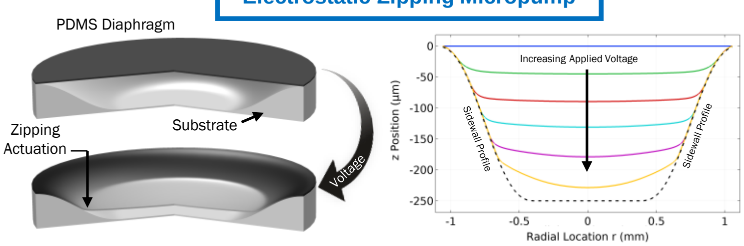


Fig. 2: Electrostatic zipping of a circular elastomer diaphragm along the curved, sloped walls of a microfluidic chamber, enabling a range of motion of several hundred micrometers.

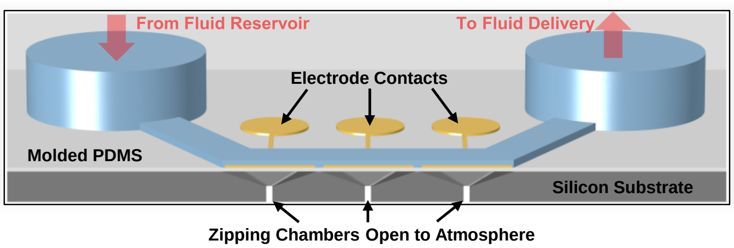
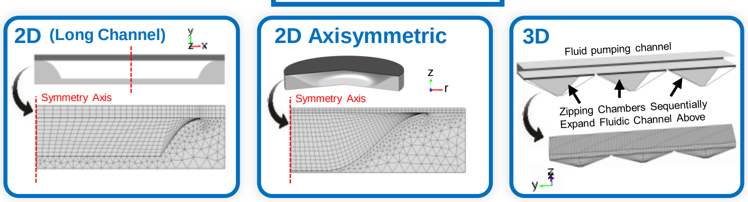


Fig. 3: Electrostatic zipping concept in a 3-chamber peristaltic micropump (diagram not to scale).

Numerical Models



Governing Equations

Navier-Stokes & Continuity: (velocity field)

$$\rho_f\left(\frac{\partial \mathbf{u}_f}{\partial t}+\mathbf{u}_f\cdot\nabla\mathbf{u}_f\right)=\eta\nabla^2\mathbf{u}_f-\nabla p$$

$$\nabla\cdot\mathbf{u}_f=0$$

Solid Mechanics: (displacement field)

$$\rho_s\frac{\partial^2\mathbf{u}_s}{\partial t^2}=\nabla\cdot\sigma_s$$

Charge Conservation: (electric field)

$$\nabla\cdot\mathbf{D}=\rho_E$$

Boundary Conditions

Substrate surface:
Fixed, grounded, no slip

Diaphragm top surface*:
Free (or match stress & velocity), applied voltage

PDMS layer sidewalls:
Fixed, zero charge

Fluid inlet/outlet:
Open boundary, zero charge

Fluid/solid interface:**
Match stress & velocity, zero charge

*Maxwell stresses also imposed on all diaphragm boundaries

**Artificial spring simulates contact between diaphragm & substrate;

Acknowledgement

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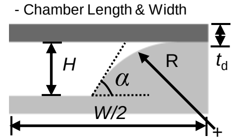
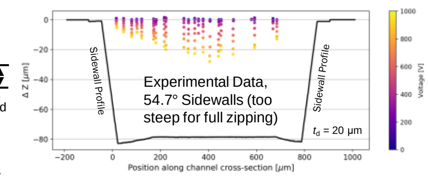
Results

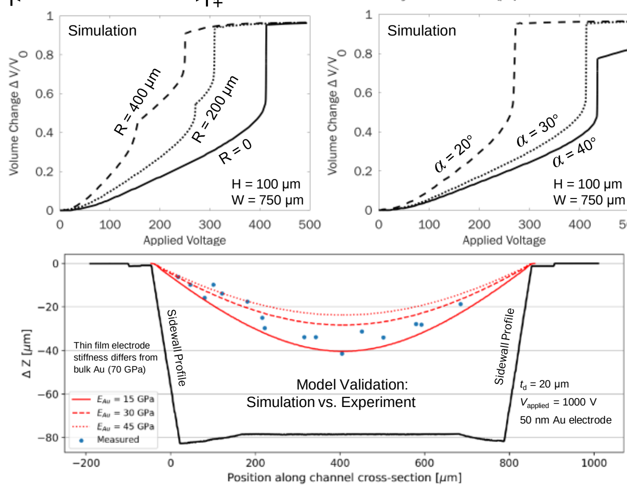
Our numerical model exhibits good agreement with our experimental results. Further, by investigating critical geometrical parameters such as the substrate sidewall angle, top corner fillet radius, and PDMS diaphragm thickness, we are able to optimize for ~100 µm deflections achievable with ~100 V. We numerically demonstrate this approach for pumping and predict possible flow rates ranging from pL/s to µL/s.

Design Considerations

- Sidewall Slope Angle
- Corner Radius of Curvature
- Diaphragm Thickness
- Chamber Length & Width







Peristaltic Pumping Mechanism

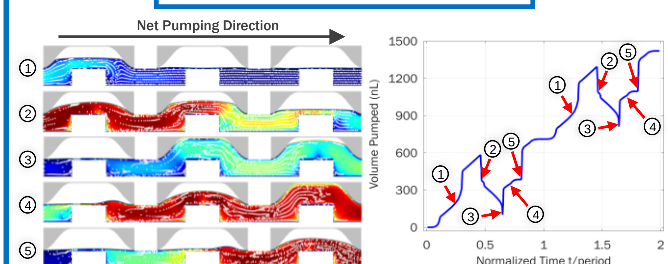


Fig. 4: Three-chamber peristaltic pumping sequence: logarithm of the velocity magnitude is plotted in color (left), along with flow throughput (right).

Conclusions

- Experimental results in good agreement with simulation for a 54.7° silicon sidewall
- Larger corner radii and smaller sidewall angles of zipping chamber in particular enable larger actuation strokes at lower voltages
- Zipping exploited for pumping concept; promising mechanism provides many potential benefits:
  - ✓ Very low power requirements (capacitive)
  - ✓ Precise, valveless fluid manipulation of small (nL-uL) volumes @ low flow rates
  - ✓ No electric field passed directly through pumped fluid

References

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