Air Damping of Oscillating MEMS Structures: Modeling and Comparison with Experiment

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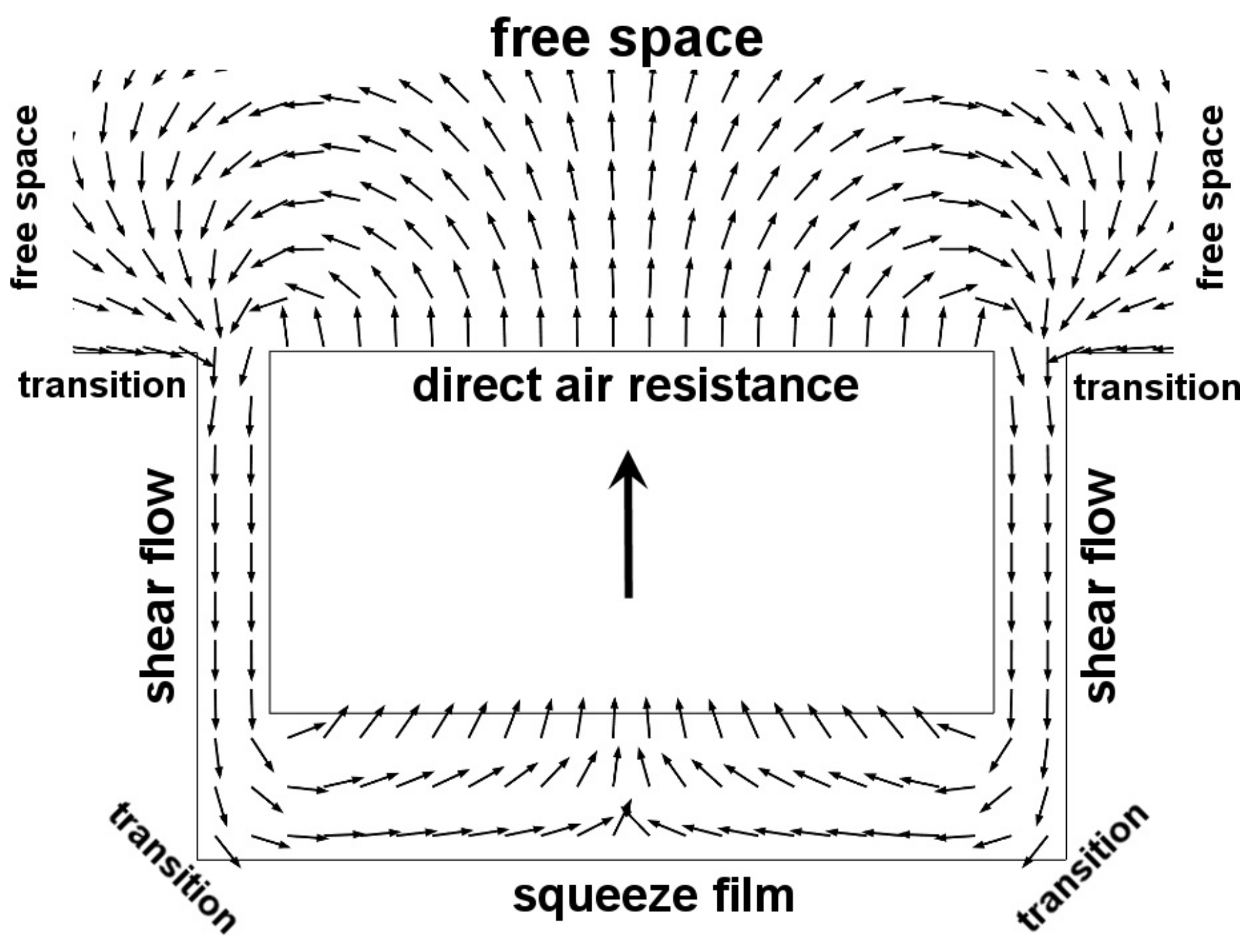
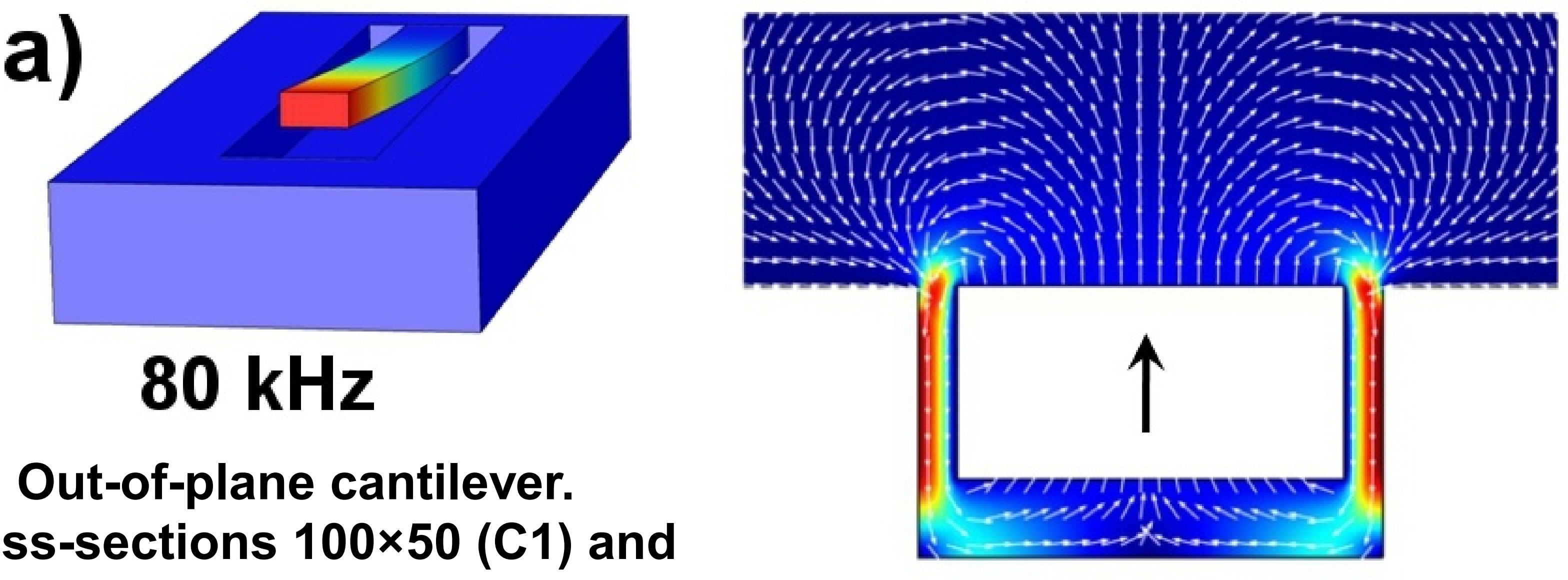
Introduction: Air damping can be detrimental to the performance of vibrating MEMS components. Quantitative evaluation of the damping is challenging due to the complex interaction of air with moving structures and typically requires numerical simulations. A full three-dimensional analysis can be computationally very expensive, time consuming and not feasible. Here, we present a simplified two-dimensional modeling of damping per unit length of selected MEMS structures. **The simulated air damping results were compared with experimental measurements of corresponding piezoactuated resonators**: in-plane and out-of-plane tuning forks, two types of out-of-plane cantilevers and a torsional micromirror. The applicability of the simplified model is verified by a good (2-30%) agreement between the simulated and measured Q-values.



The simulated systems aimed at modeling the air damping of selected MEMS devices. The test devices were fabricated using c-SOI technology (cavity Si on insulator). **The air flow damping invloves several types of flow.** The devices were actuated by means of thin (1 µm) aluminium nitride piezolayers processed on top of the released structures.

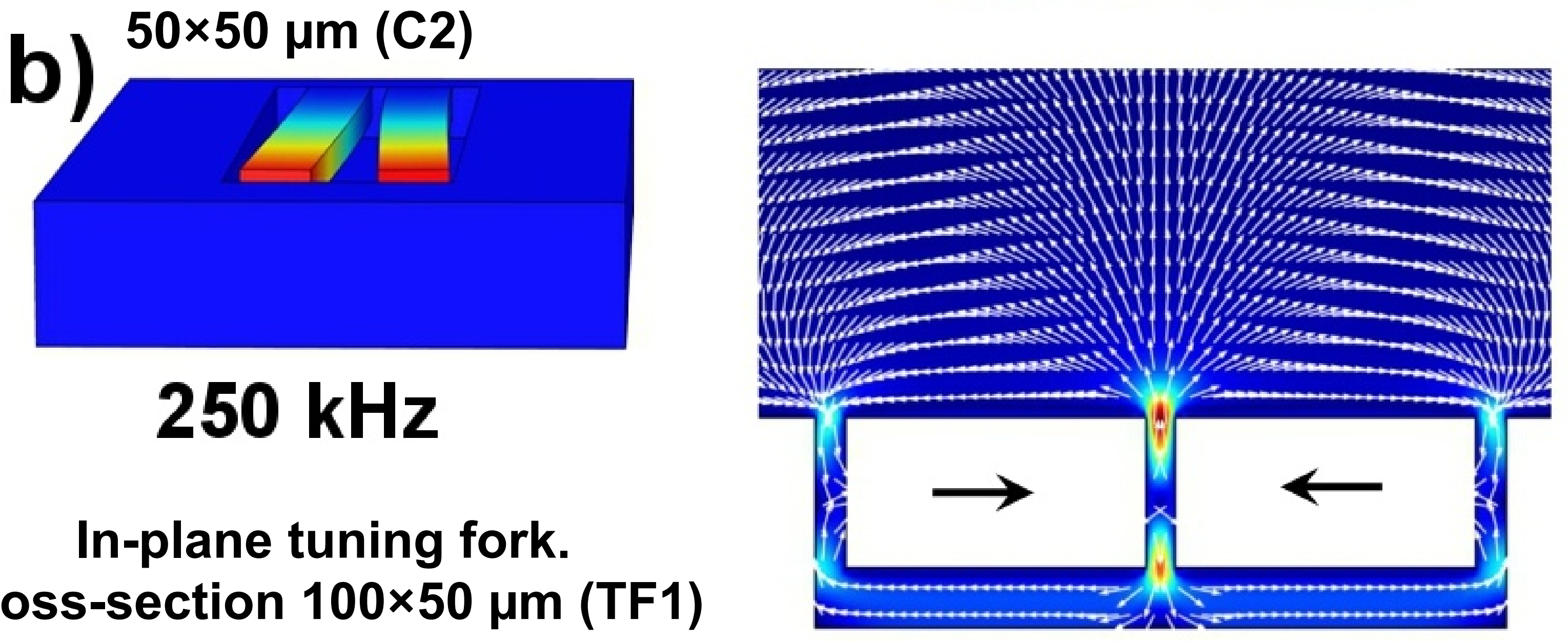
a)



80 kHz

Out-of-plane cantilever. Cross-sections 100×50 (C1) and 50×50 µm (C2)

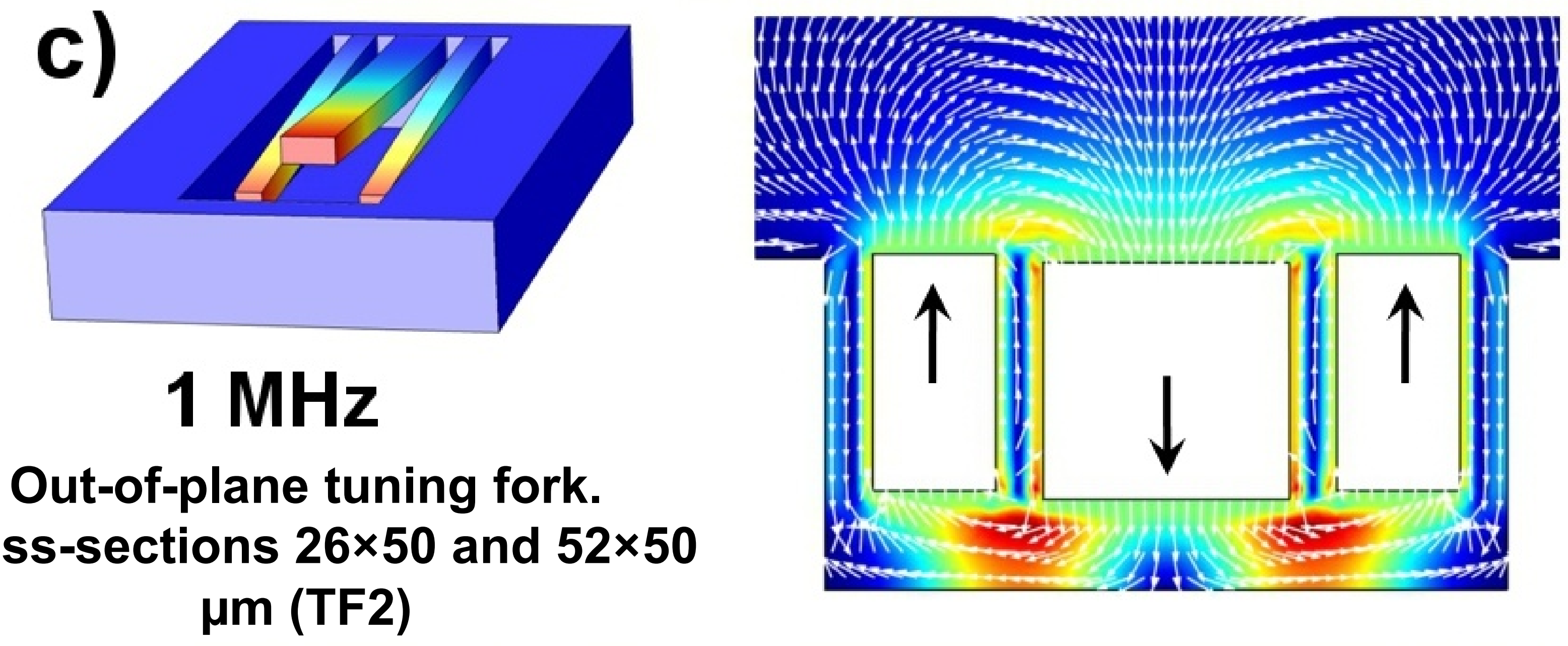
b)



250 kHz

In-plane tuning fork. Cross-section 100×50 µm (TF1)

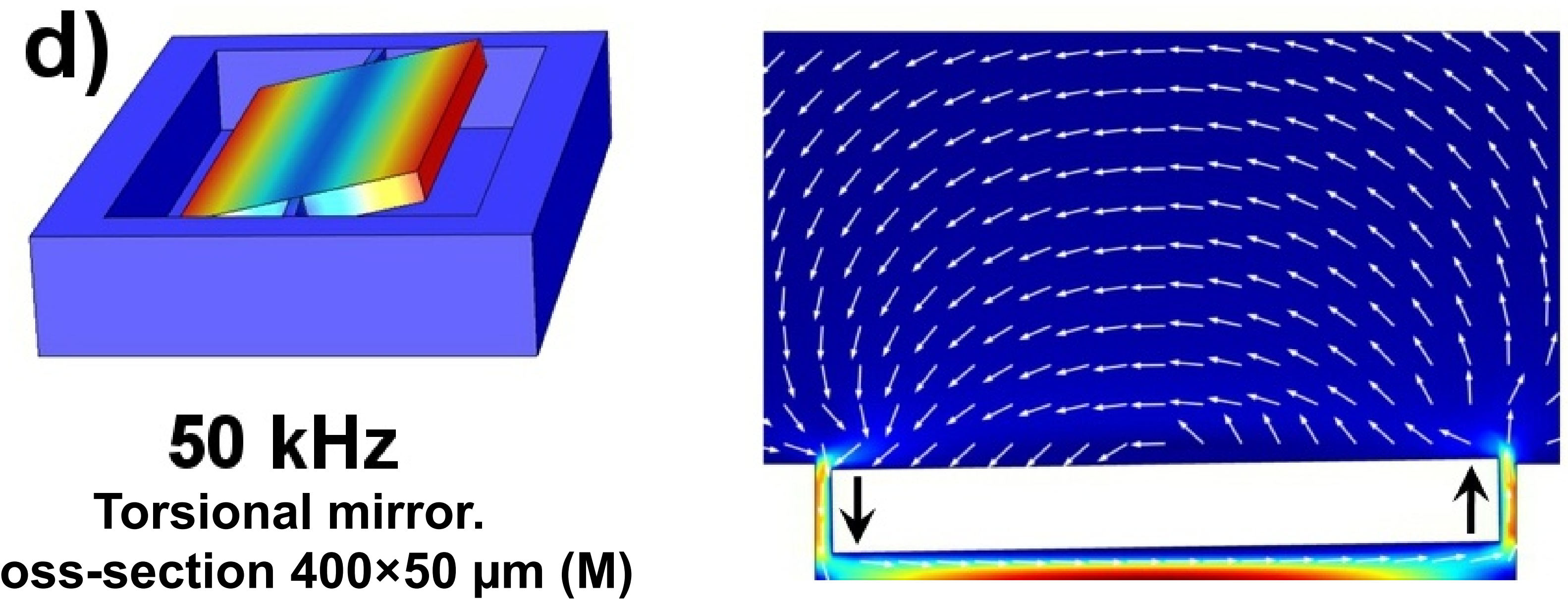
c)



1 MHz

Out-of-plane tuning fork. Cross-sections 26×50 and 52×50 µm (TF2)

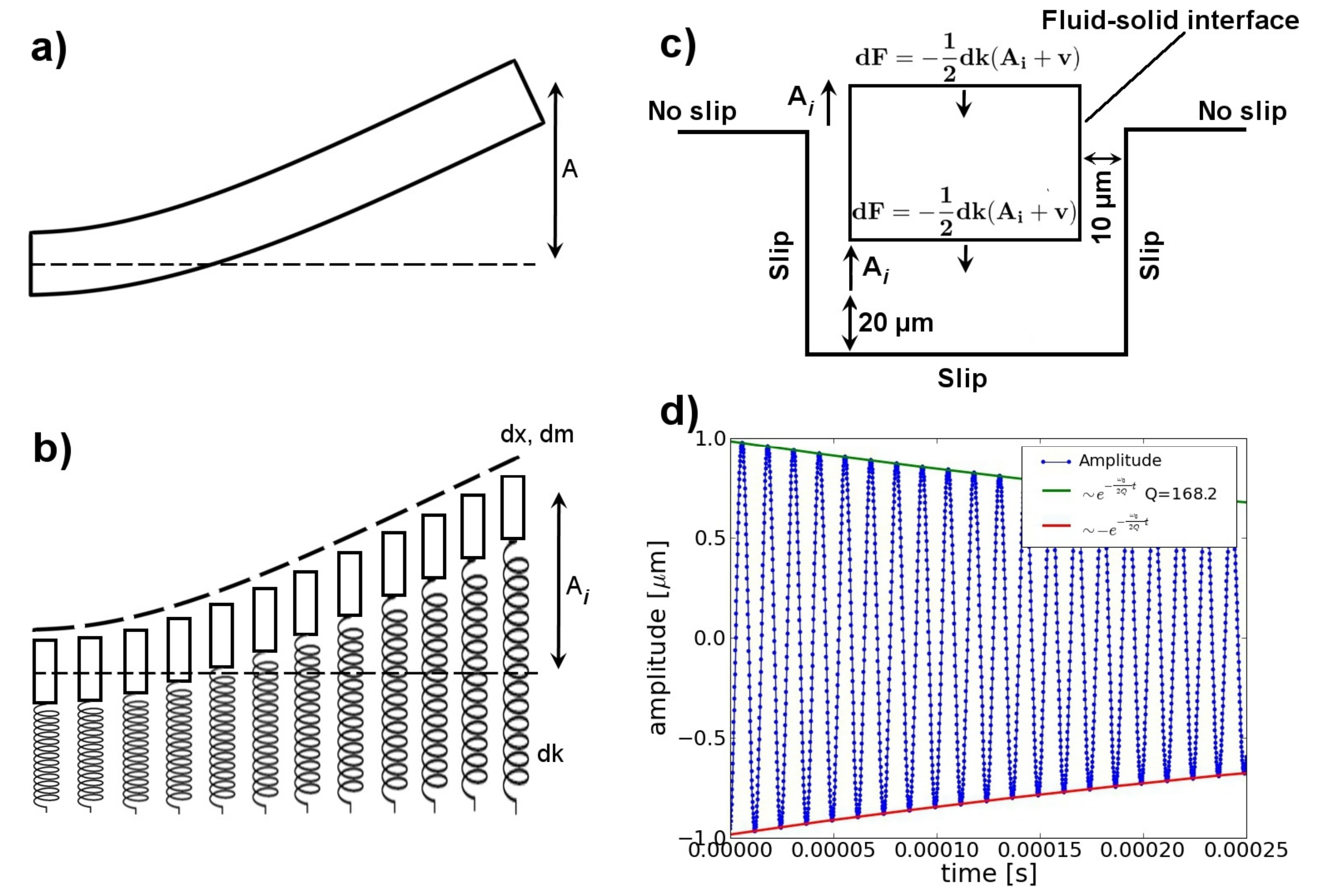
d)



50 kHz

Torsional mirror. Cross-section 400×50 µm (M)

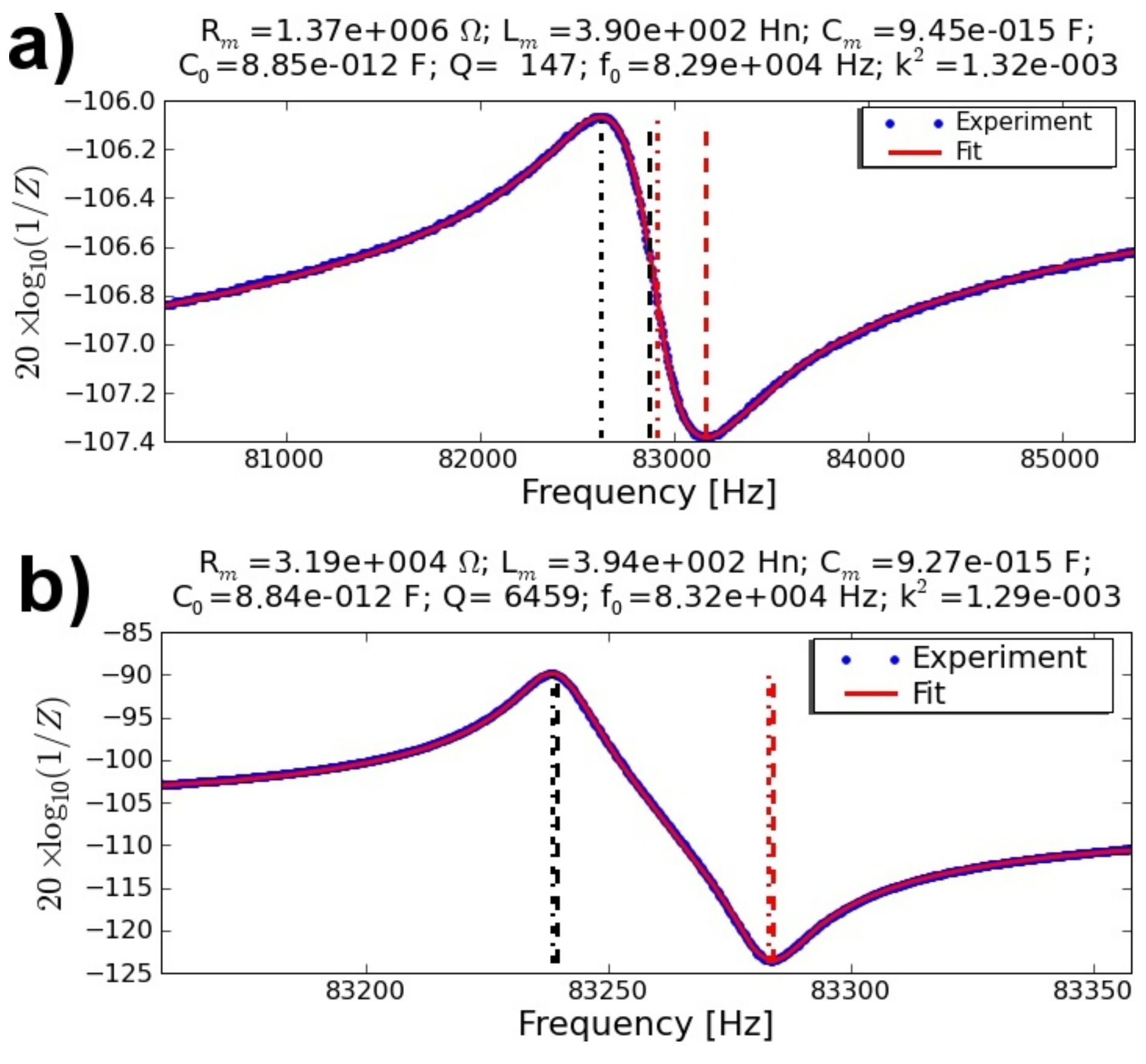
Simplified 2D COMSOL flow model: Initially deformed beam with a tip displacement *A* is subdivided into narrow cross-sections of width *dx* and mass *dm*, each displaced by an intial amplitude A_i, such that the envelope of the $\{A_i\}$ resembles the initial mode shape of the beam. The cross-sections oscilate vertically and synchronously at the resonance frequency of the original beam due to the action of numerical spring forces *dk*. The approximation is justified if the beam length is much greater than its other dimensions (the air flow profile can be assumed 2D), and the flow is laminar with negligible interaction of air flows induced by neighbouring cross-sections. The simulations were in time domain. The Q-values were estimated from the logarithmic decrement of the amplitudes A_i.



Reynolds number (Re): 0.01…5.27. The flow is laminar.

Knudsen number (Kn): 3.5…7×10^{-3} (gap sizes are 10-20 µm). Slip flow dynamics is more applicable.

Mach number (M): Max velocities are < 8 m s^{-1} (<< 330 m s^{-1}). Incompressible flow.



Experimental characterisation: The characterisation of the devices was based on measuring their electrical frequency-admittance curves around the resonance. The mechanical Q-values both in vacuum and air were derived from the $R_m L_m C_m$-C_0 equivalent circuit fits. Damping due to the viscious damping force (Q in air) is then

$$\frac{1}{Q_{air}} = \frac{1}{Q_{flow}} + \frac{1}{Q_{vacuum}}$$

device	f0, kHz	Q in air	Q vacuum	Q flow	Q simulated	Agreement
C1	80	150	6500	153	168	91%
C2	80	180	6530	185	265	70%
TF1	250	1200	40000	1240	1190	96%
TF2	1000	5600	16000	8615	8820	97%
M	50	175	50000	176	214	82%

The studied test systems involve various types of motion within pre-etched cavities (**in-plane**, **out-of-plane**, **torsional**) and in a wide range of frequencies (**10^4…10^6 Hz**). The Q-values from simplified 2D simulation agree very well with the experimentally measured values. The good agreement of the simulation and experiment validates the model and its applicability for modeling of air damping in other MEMS systems.

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