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A novel piezoelectric MEMS speaker with push-pull actuation for in-ear applications

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Summary:
This work introduces an innovative high-performance push-pull piezoelectric Micro-Electro-Mechanical System (MEMS) loudspeaker for in-ear applications. It consists of a diaphragm featuring narrow slits and covered with two distinct piezoelectric patches that are actuated with a 180° out-of-phase sinusoidal signals to increase its maximum displacement. The device delivers a Sound Pressure Level (SPL) of up to 109.5 dB SPL from 100 Hz onward with an excitation of 30 Vpp, shows a Total Harmonic Distortion (THD) of 0.8% at 1 kHz and at 94 dB SPL, and maintains a compact square footprint of 4.5 x 4.5 mm².

Keywords: Push-pull actuation, Piezoelectric thin film, Micro-speaker, IEC 60318-4 coupler.

Introduction

Loudspeakers are key components of modern audio systems, with MEMS variants offering compact, low-power solutions ideal for devices such as smartphones, wearables, and hearing aids.

Piezoelectric MEMS speakers stand out for their high driving forces achievable at low voltages, attracting growing scientific interest. These devices generally consist of a suspended diaphragm actuated exploiting the inverse piezoelectric effect and various methods have been explored to further improve their mechanical and acoustic performance. A key example is the mechanically open, acoustically closed (MOAC) design principle [1], which adds openings to the diaphragm to lower stiffness and increase elongation, while narrow gaps retain enough air resistance to prevent acoustic leakage.

Another recent advancement is the out-of-phase activation of separate piezoelectric patches [2]. Despite requiring more complex wiring, these patches can be positioned strategically to increase the diaphragm total displacement while keeping the same piezoelectric capacitance.

Both these concepts are applied for the design of a new high-performance prototype that was numerically simulated, fabricated and tested. The speaker of this work achieves a SPL greater than 109.5 dB SPL from 100 Hz onward with a bias voltage of 15 V_{dc} and two alternate voltages of 30 V_{pp} and opposite phase, and a THD of 0.8% at 1 kHz and 94 dB SPL.

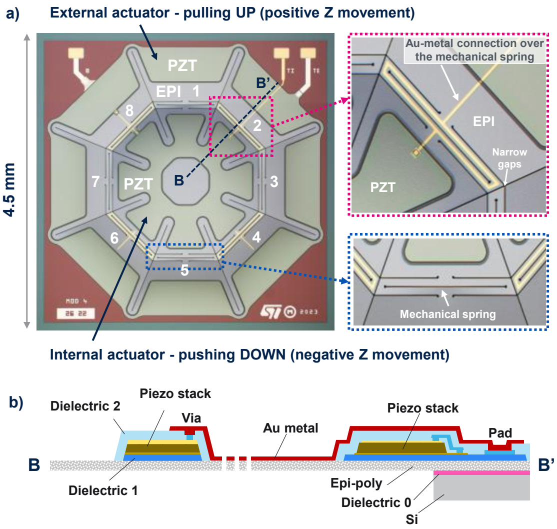

Fig. 1. a) Optical microscope view of the MEMS speaker with details of the Au-metal connection and mechanical springs, b) Schematic of its cross section.

Working principle

The MEMS loudspeaker is shown in Fig. 1a, while a schematic of its cross section is reported in Fig. 1b. The design features eight trapezoidal plates fabricated from a 13 µm thick layer of Epi-Poly, separated by 5 µm narrow slits to reduce acoustic short-circuits [3], and partially coated with a 2 µm thick film of Lead Zirconate Titanate (PZT) with a piezoelectric capacitance of 35 nF, forming the external actuator. These plates are attached to the device's central portion via mechanical springs and secured to an external, fixed frame, resulting in a total footprint of 4.5 x 4.5 mm².

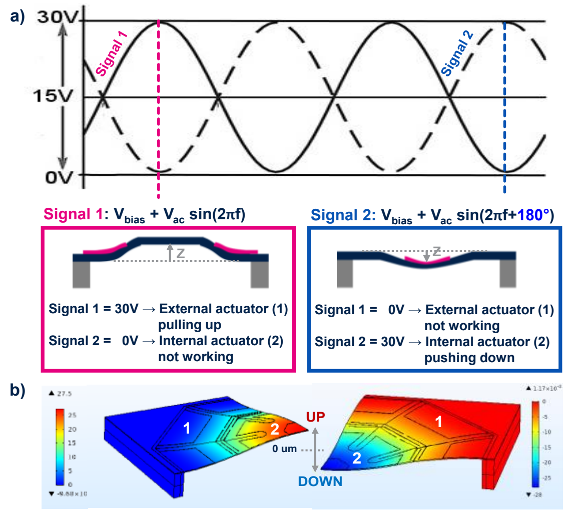

Fig. 2. a) Schematic of both pulling up and pushing down actuations represented with the relative electric signals in opposition of phase. b) Finite Element Method (FEM) simulations of the resulting static displacements considering an excitation of 30 V.

An additional 2 µm thick PZT patch covers the central portion as well and forms the internal actuator, with a lower capacitance of 15 nF, and a dedicated Au-metal electrical connection integrated along the mechanical spring. As shown in Fig. 2, this structure allows a bidirectional movement: actuating the external patch causes the trapezoidal plates to bend upward (pulling up), while actuating the central patch causes the central portion to bend downward (pushing down). The independent electrical connections allow to excite the two actuators with a 180° phase difference, resulting in alternating upward and downward movements in a push-pull actuation. The resulting maximum deflection is the sum of the two modes actuated separately, and as shown in Fig. 3 it surpasses the deflection achievable with a standard single-patch actuation. Moreover, the total piezoelectric capacitance is kept lower or equal to 35 nF during the whole actuation as the maximum excitation voltage is never applied contemporary to both patches.

Results

The device was numerically modeled through the FE software COMSOL Multiphysics, fabricated and tested with the experimental setup reported in [3]. The result in terms of SPL is reported in Fig. 4 together with another our MEMS speaker used as reference with piezoelectric capacitance of 35 nF and same footprint of 4.5 x 4.5 mm² but actuated by a single PZT patch. The new push-pull design was actuated with a bias voltage of 15 V_{dc} and two alternate voltages of 30 V_{pp} and opposite phase, applied separately to the two patches. The speaker reaches up to 109.5 dB SPL from 100 Hz onward, with a THD of 0.8% at 1 kHz and at 94 dB SPL.

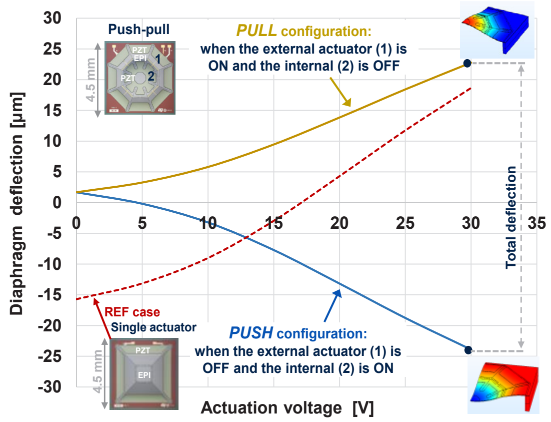

Fig. 3. FEM estimation of the static displacement from pulling up and pushing down actuations, compared with a standard single piezoelectric actuator with equivalent piezoelectric capacitance of 35 nF.

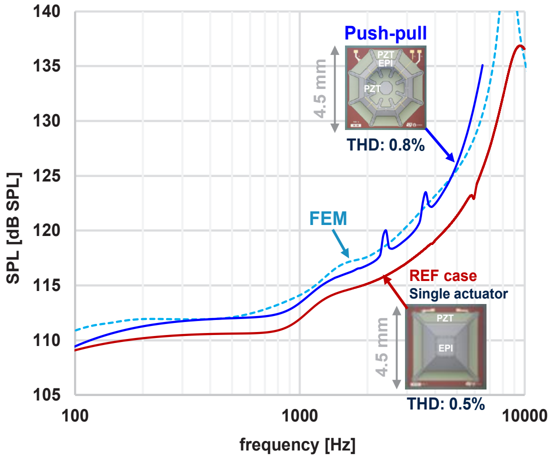

Fig. 4. Comparison of the experimental (solid lines) and numerical (dotted line) SPL measured in-ear conditions between the piezoelectric speaker with push-pull actuation and a traditional speaker with a single PZT patch, for a bias voltage of 15 V_{DC} plus an alternate voltage of 30 V_{pp}. THD of 0.8% measured at 1 kHz and at 94 dB SPL.

The SPL is incremented by 0.4 dB SPL at 100 Hz and by 1.5 dB SPL at 1 kHz with respect to the compared device.

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