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Tunable passband T-filter with electrostatically-driven polysilicon micromechanical resonators

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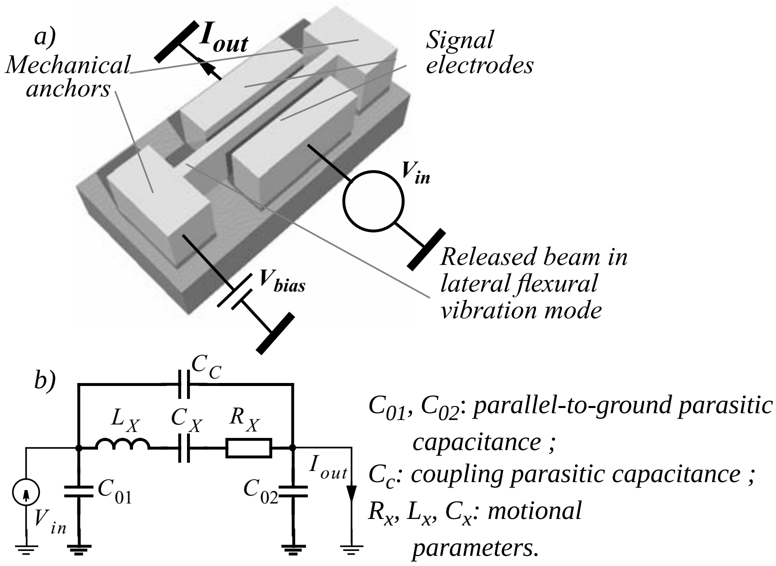
Abstract. A 2.4 MHz tunable bandpass T-filter built from three micromechanical silicon-micromachined electrostatically-driven resonators is demonstrated for the first time. Non-linear properties of electrostatical transducers are used to obtain a voltage-control of the transmission zero and pole distribution; a novel charge biasing technique is employed for electrostatical transducer biasing. Transmission zero frequency tuning is demonstrated.

Key words: T-filter, passband, electrostatically driven resonators, transmission zero, tunable

Introduction. Integrated silicon-micromachined electrostatically driven tunable micromechanical filters are potential candidates to replace bulky SAW filters in IF stages of radioreceivers. Up to now only simple coupled-resonator filters have been presented, with “all pole” transmission characteristics [1], [2]. The presented structures were equivalent to LCR electrical ladder networks including series RLC sections (i. e. elementary resonators) in horizontal branches of the ladder. However, transmission zeros placed at adjacent channel frequencies can considerably alleviate requirements toward overall IF filter selectivity. In the electrical domain, this can be achieved by incorporating series RLC networks (elementary resonators) in vertical (parallel) ladder branches. In the elementary case of three-resonators filter this yields a so-called T-topology (fig. 1a); widely used with BAW and quartz resonators [3], this architecture has never been realized with electrostatically-driven micromechanical resonators.

This letter presents a tunable T-filter built from three micromechanical electrostatically-driven resonators realized in a thick-film epitaxial polysilicon micromachining technology of ST Microelectronics characterized by a 15 µm thickness structural layer [4]. Unlike its counterparts based on quartz or BAW resonators, this filter requires external high-impedance DC biasing for the electrostatical transducers. In our structure, this is achieved using a novel constant charge biasing technique. The measurement results firstly demonstrate a filter transmis-



C_X=0.46 fF, R_X=27 kΩ, Q=6000 at V_{bias}=30 V, C_C=5-7fF,
C_{01}=C_{02}=0.12 pF

Fig. 1. Elementary resonator: a) mechanical architecture, b) equivalent electrical network.

sion characteristic with transmission zero, whose frequency is controlled by a bias voltage.

Elementary resonator operation. The filter uses three resonators with identical geometry (fig. 1a). Resonators include a vibrating element implemented with a clamped-clamped beam vibrating in lateral mode (parallel to substrate), and a pair of input-output electrostatical transducers formed by the walls of the signal electrodes and the resonator. DC biasing is necessary to linearize the quadratic transducing function and to increase the electromechanical coupling factor of the transducers. The AC input voltage is applied to the input transducer, creating a variable input force on the vibrating element. The resonator response is transformed to current by the output transducer. In the electrical domain such a resonator is seen as a series RLC network with three parasitic capacitors (fig. 1b). The motional parameters of the resonator depend both on resonator geometry and the bias voltage, making it possible to tune the resonance frequency. The important numerical parameters of resonator used in the implemented filter are given in fig. 1. A detailed study of the device can be found in [5, 4, 6].

T-filter architecture. An T-filter is composed of three elementary resonators (fig. 2). The series resonance of the resonators 1 and 2 and the parallel resonance of the resonator 3 generate the filter passband poles, and parallel resonance of the resonators 1 and 2 and the series res-

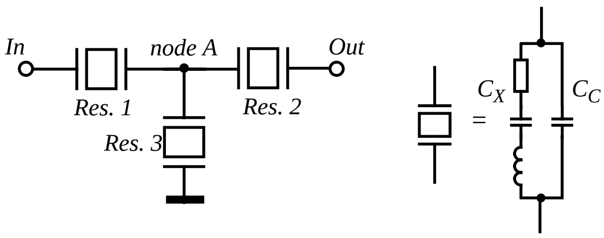


Fig. 2. Architecture of an elementary T-filter.

onance of the resonator 3 generate the filter transmission zeros [3]. For each resonator the ratio between the series and parallel resonance frequencies (f_S and f_P) depends on the ratio between the motional and parallel capacitances (C_X and C_C):

$$f_P = f_S\sqrt{C_X/C_C + 1}\,. \tag{1}$$

Series resonance frequency is defined by the vibrating element resonance frequency f_0, the transducer parameters (bias voltage *Vbias*, transducer's area *S*, transducer's gap d_0) and the mechanical stiffness of the vibrating element k_0:

$$f_S = f_0 \cdot \sqrt{1 - \frac{V_{bias}^2 \varepsilon_0 \frac{S}{d_0^3}}{k_0}}\,. \tag{2}$$

Details on T-filter design issues can be found in [3]. Although this monography principally adresses electrical filter design, the proposed techniques can be re-used with mechanical filters by employing electromechanical analogy (approach demonstrated in [1], [5]).

By contrast with piezoelectric electromechanical transducers, electrostatical transducers need a DC voltage biasing for linear-mode operation. At the same time, the biasing should preserve the high-impedance state of the signal node A.

T-filter realization. In the realized filter (fig. 3) the resonating beams are biased by DC voltages V_{r1}-V_{r3}. The external electrodes of the input-output transducers are zero biased thanks to the resistors R_L and R_S providing a DC path to ground. High-impedance voltage biasing of node A could be achieved using a high-value choke inductor or resistor. It isn't practical here: (i) high-value elements are undesirable in integrated circuits, (ii) external connections to this node dramatically increase its parasitic capacitance. Instead we propose to use the technique of constant-charge biasing of electrostatic transducers [2], [5]. It employs a micromechanical switch to connect node A with a DC voltage source for a time enough to charge all node capacitances (transducer and parasitic). This operation allows to define an initial potential of node A. When the switch is off, the node charge remains constant but redistributes among the resonators when they move. This redistribution modifies the potential of node A and so the force generated by each transducer thus creating a mechanical coupling between the resonators [6, 5].

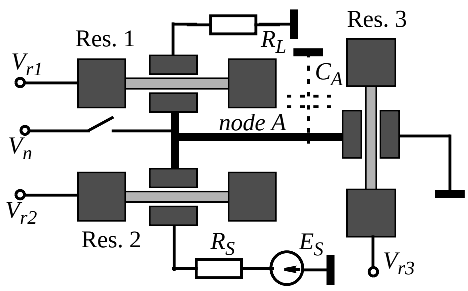


Fig. 3. Architecture of the realized filter. C_A is a parasitic parallel-to-ground capacitor.

The C_X/C_C ratio of elementary resonators is relatively high, resulting in parallel resonance frequency of resonators approximately 100 kHz above the series resonance frequency (cf. eq. (1)). In fact, the intrinsic C_C capacitance is due to the electrostatic coupling between the resonator electrodes, and intrinsically weak (5-7 fF, cf. fig. 1). However, in the realized filter prototype the resonator 3 has a relatively high external capacitance due to the 0.36 pF parasitic parallel-to-ground capacitance of node A (C_A in fig. 3) which yields a pole-to-zero offset of ~1.5 kHz for this resonator. Therefore, the filter will have only one useful transmission zero close to the passband generated by the series resonance of the resonator 3; two others (generated by the parallel resonance of the resonators 1 and 2) appear far from the passband and can’t be observed. To approach the parallel resonance frequency of the resonators 1 and 2 close to the center of the passband, external coupling capacitances should be used; this will add two additional useful transmission zeros and increase the filter selectivity.

The photo fig. 4 presents the overall view of filter, and enlarged views of an elementary resonator and switch. The complex geometry of the transducer electrodes realizes a post-fabrication reduction of the large lateral transducer gaps obtained at fabrication. For this the resonator electrodes are released, joined to a soft released spring and attracted close to the beam by an electrostatic actuation [4]. The electrode motion is limited by stoppers. The gap is reduced from 3.0 μm down to 0.5 μm.

The mechanical switch is realized on the same chip as the resonators, its operation is similar to that of the gap reduction mechanism. The contact electrode is released, joined to a soft spring and pushed with a pair of electrostatic transducers so get in contact with a plane of the node to be biased (node A). Stoppers protect the switch actuators from the short-circuit; in difference with the gap reduction mechanism, the motion of the contact electrode is limited by the node A plane, not by the stoppers. The direct proximity of the switch with the node A allows to minimize the parasitic capacitances on the latter. The actuation voltage equals 40 V [2].

Filter fabrication. A vertical section of a device fabricated in thick-film epitaxial polysilicon technology is presented in fig. 5. A device is built with two polysilicon layers, one is the 15 μm thickness structural layer, the second is 0.45 μm thickness buried layer used for anchor-

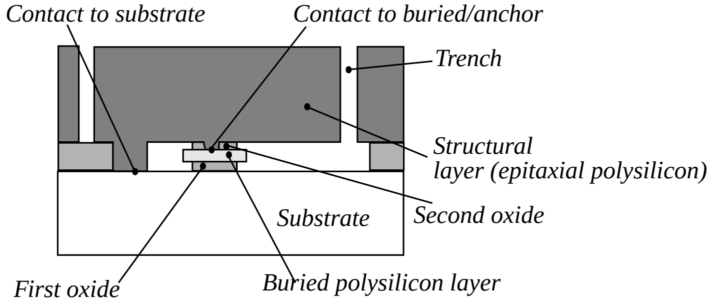


Fig. 5. Section of a device in thick-film epitaxial polysilicon technology.

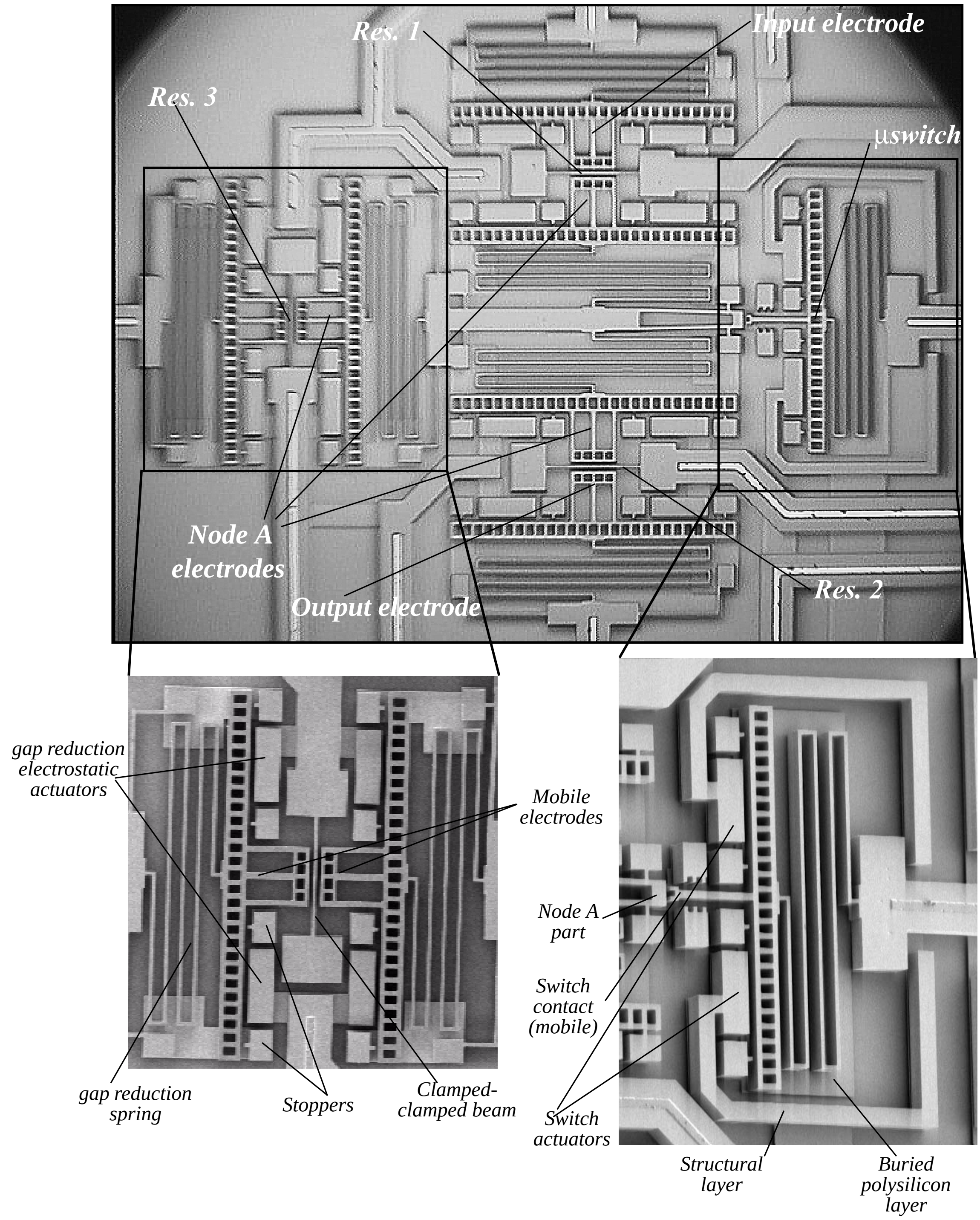


Fig. 4. Photo of the realized filter with enlarged view of an elementary resonator and switch.

ing and interconnect (cf. also fig. 4). The devices are machined in the structural layer by anisotropic dry etching. The mobile parts are released using time-controlled releasing technique.

Experimental results. The filter was terminated by a 50 Ω resistor at the input and a 1 kΩ resistor at the output port, the output voltage was amplified by a 20 db gain voltage amplifier. The filter was tested in a vacuum chamber under 0.1 Torr air pressure. At the used bias voltages, the individual resonator impedance is about 30-40 kΩ, thus correct filter termination would require source and load impedances of hundreds kiloohms at filter ports. In our case this was impossible to realize because of the large parasitic capacitances of the measurement setup. For this reason the low measured filter transmission -(21+20) db doesn't represent the insertion loss of a correctly terminated filter. Thus, the main damping mechanism is related to the internal losses of resonators defined by their quality factror (5000 measured at 0.1 Torr pressure).

The control of the transmission characteristic shape is achieved in the following way. Voltages V_{r1}, V_{r2} allow to correct the resonance frequency mismatch of the resonators 1 and 2 due to the fabrication tolerances. Thanks to the voltage V_n, we can control the coupling factor between these resonators, thus the passband pole distribution which defines the filter bandwidth [2]. This voltage was fixed to 18.10 V so to obtain a maximally-flat passband when the resonators have a quality factor of 5000. Detailed characterization of the bandwidth control of a two-resonator charge-biased passband filter (without transmission zero) has been presented in [7], a 8.9 max-to-min bandwidth control ratio has been achieved.

V_{r3} controls directly the series resonance frequency of resonator 3, thus the filter zero frequency. The plots in fig. 6 present three measured filter transmission characteristics for different bias voltages of resonator 3 (V_{r3}), demonstrating the possibility to control the transmission zero frequency.

We should note a very high sensitivity of the filter characteristic with respect to the bias voltages (10 mV precision was required in the experiment). This can be explained by the very high overall quality factor of the filter and thus by the very high required relative precision of the pole and zero implementation.

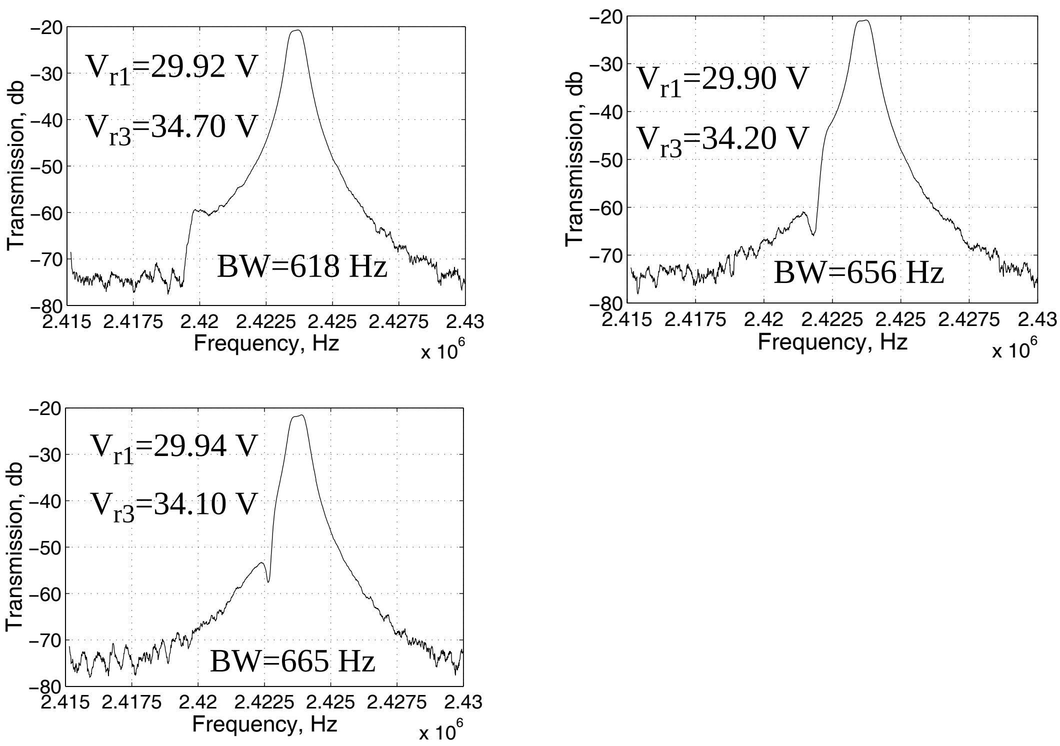


Fig. 6. Filter transmission characteristics: V_n=18.10 V, V_{r2}=20.5 V.

Conclusions. This work shows that complex filtering architectures having large tuning potential are possible with electrostatically-driven micromechanical resonators. Thank to the constant-charge biasing of electrostatical transducers, filter networks constructed with piezo-electrically-driven resonators are realizable with electrostatically-driven resonators. We demonstrated a prototype of a 2.4 MHz electrostatically-driven T-filter with reconfigurable transmission characteristic. For the first time, zero frequency tuning was demonstrated for a microelectromechanical passband filter.

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Figure titles

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