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A Protocol for Automated Passband Correction of High-Order Microelectromechanical Filters

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***Abstract*— A systematic protocol for filter passband correction, together with voltage-controlled frequency tuning provided by capacitive-gap transducers, has made possible a 4-resonator micromechanical filter with a 0.1% bandwidth commensurate with the needs of channel-selection and an impressive 20-dB shape factor of 1.59. Indeed, a filter with this small a percent bandwidth would yield very poorly without this tuning mechanism and correction protocol, since typical finite fabrication mismatch tolerances on the order of 300ppm do not permit an undistorted filter passband without post-fabrication tuning. Although demonstrated at a medium frequency (MF) of only 523.5 kHz, this filter passband correction protocol is directly applicable to higher frequency small percent bandwidth filters targeted for ultra-low power RF channel-selecting communication front-ends. An automated computer-controllable passband tuning protocol like that demonstrated here is among the more important ingredients needed to realize an RF channel-selecting filter bank.**

Keywords—MEMS; micromechanical; filter; tuning; high-order; channel-select

I. Introduction

As interest in ultra-low power radios for sensor networks increases, so does a similar interest in small percent bandwidth frequency filters capable of selecting individual RF channels while rejecting all other channels, even those traditionally considered in-band [1]. Indeed, if such filters were feasible, radio receiver front-end circuits could dispense with the overdesign often needed to insure sufficient dynamic range against strong interfering signals that would otherwise desensitize them. The result would be a substantial reduction in the power consumed by such circuits.

To date, no high volume (inexpensive) filter technology can yet achieve the described RF channel-selection with adequate performance, although some might be on the verge of this. In particular, filters employing high Q capacitive-gap transduced vibrating resonators, such as that of [2], have actually achieved adequately low insertion loss when passing the needed 0.1% bandwidth. However, they unfortunately require improvements in electromechanical coupling to attain the needed >50dB stopband rejection. They are also in need of some way to improve yield, which becomes ever more difficult when percent bandwidths are only 0.1%.

To expand on this, a 0.1%-bandwidth 455-kHz 0.5dB-ripple 4-resonator Chebyshev filter employing quarter-wave couplers between (ideally) identical resonators requires that the resonators be matched to no worse than 137ppm to avoid additional passband ripple (over the design value) of more than 0.5dB. Given that resonators from [3] fabricated using a university nanofabrication facility post device-to-device frequency standard deviations on the order of 315ppm, it seems unlikely that RF channel-selecting filters with adequately small passband ripple can be manufactured with sufficient yield for high volume production. Indeed, unless industrial microfabrication facilities can do substantially better than their university counterparts, some form of frequency tuning or trimming will be needed. Inevitably, it is likely not a question of whether or not trimming or tuning is needed, but rather what protocol can most efficiently correct the passband response.

Towards answering this question, this work employs electrical stiffness-based voltage-control of capacitive-gap transduced resonator frequency [4] to explore an automated tuning protocol bent on maximizing the integrated energy in the filter response spectrum. The method lends itself well to iterative convergence, where the change in integrated energy induced by a small tune in one direction immediately confirms or rejects that direction, hence, governs the direction needed for the next tune increment. Use of this tuning protocol yields a 4-resonator micromechanical filter (*cf.* Fig. 1) with a 0.1% bandwidth commensurate with the needs of channel-selection (albeit at a low frequency) and an impressive 20-dB shape factor of 1.59, all with less than 3dB of additional passband ripple (beyond the design ripple).

II. Coupled Resonator Filter Operation

Before detailing the tuning protocol, it is instructive to first review the structure and operation of the filter-to-be-tuned, shown in top-view in Fig. 1. Here, the demonstrated filter is similar to that of [5] in its use of capacitive comb-driven ratioed-folded-beam resonators coupled at low-velocity locations via flexural mode beams. In the preferred operation scheme, the combination of a DC-bias voltage V_P and AC input voltage v_i applied through a proper termination resistance across the electrode-to-resonator comb of the left-hand-side end resonator generates a force at the frequency of v_i amplified by the magnitude of V_P. This force in turn produces an input vibration (i.e., a mechanical signal) on the left-hand-side resonator that traverses the filter transfer function, get-

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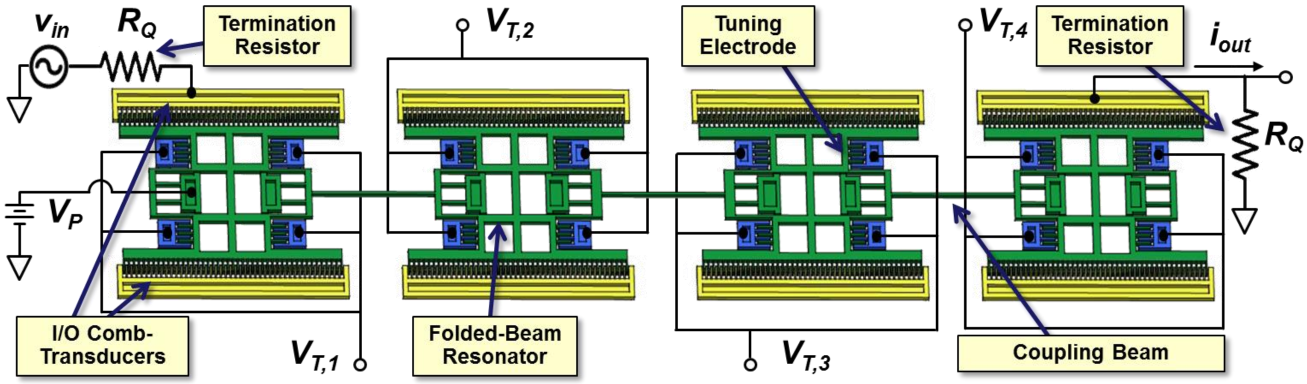

Fig. 1 Top-view schematic of the 8-pole micromechanical filter in a single-ended drive and sense configuration and equipped with frequency tuning electrodes to allow for passband correction using an automated tuning protocol.

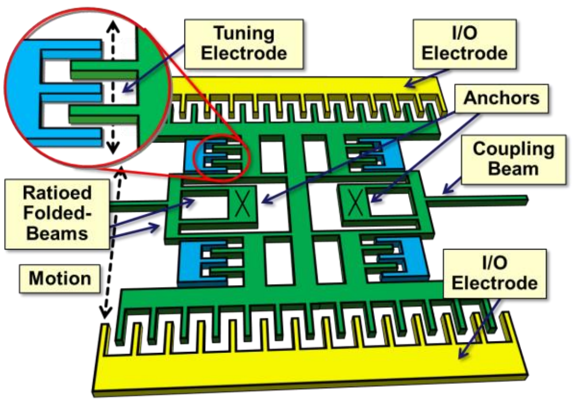

Fig. 2: Perspective-view illustration showing details of the capacitive comb-driven folded-beam resonator used in the multi-resonator filter.

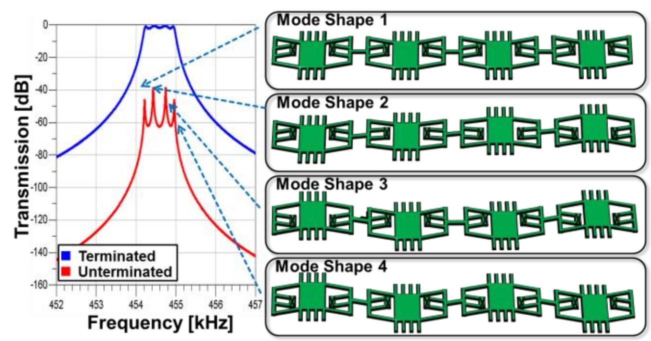

Fig. 3: Simulated terminated and unterminated four-resonator filter passband alongside the system's vibrational mode shapes.

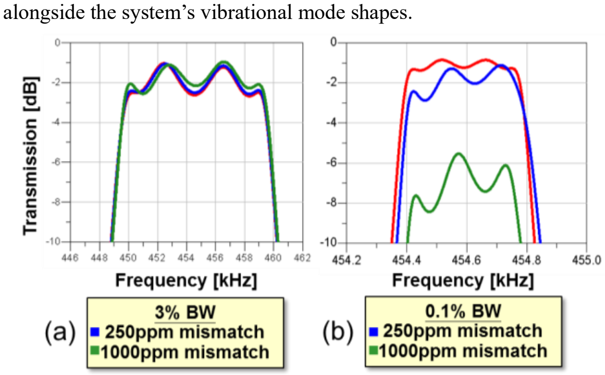

Fig. 4: Simulations illustrating the effects of mismatching of a single resonator in a 4-resonator filter with percent-bandwidths of (a) 3% and (b) 0.1%. Here, the passband distorting effect of frequency mismatch is much larger for smaller percent-bandwidth.

ting shaped in the process into a corresponding output vibration at the right-hand-side end resonator. Vibration of the right-hand-side end resonator effectively realizes a DC-biased time-varying capacitor that converts the mechanical velocity signal to an electrical output current $i_o = V_P\,(dC/dt)$. This current feeds into the output load, generating a corresponding voltage output. In effect, this filter takes an input voltage, converts it to a mechanical signal, processes the signal in the mechanical domain, then converts the signal back to an electrical signal to be forwarded to the next block in the system.

Reference [5] already presents a full description of the design and modeling of this type of filter, so rather than cover such details, this paper focuses on filter passband correction via tuning of each constituent resonator. In particular, in this design the resonance frequency of each constituent resonator is tunable via voltage-controlled electrical springs [4] generated by the parallel-plate electrodes indicated in the zoom-in of Fig. 2, which presents the perspective-view schematic of one of the constituent resonators. The overall filter described here uses more resonators than that of [5], so achieves a better shape factor, i.e., a sharper roll-off from passband to stoband. From a simplistic perspective, the first four lateral vibration modes of this 4-resonator system, shown in Fig. 3, generate the 4^{th} order, 8-pole passband shown. To flatten the mode peaks of Fig. 3 into the more familiar flat passband normally seen (*cf*. Fig. 4(a)), termination impedances R_Q, shown in Fig. 1, are incorporated into the test circuit.

All resonators in Fig. 1 are designed to have identical stand-alone frequencies, while the springs that couple them serve to split their frequencies apart to form the multiple-mode passband of Fig. 3. Here, the better matched the resonator frequencies, the more correct the passband. On the other hand, the smaller the bandwidth of the filter, the higher the degree of resonator matching needed to avoid passband distortion

Fig. 4 illustrates how a wide 3% bandwidth filter response is relatively immune to resonator mismatches on the order of 1000ppm, but the passband of a small 0.1% percent bandwidth filter is quite sensitive to even small mismatches down to 250ppm, which is on the order of what is measured for disk resonators fabricated in a university microfabrication laboratory [3]. Clearly, the 0.1% bandwidth filters demanded by RF channel-selection require matching better than so far demonstrated in fabrication, i.e., matching that would be difficult to achieve without trimming or tuning.

III. Tuning Protocol

If tuning is required, then arguably voltage-controlled tuning is most desired, since it is more convenient than laser trimming or other methods, and it can be done in real-time, anytime. The tuning process should also be fast and efficient, and if possible, automated. Indeed, although "eye-balling" the spectrum on a network analyzer while hand-tuning was sufficient for the 2nd and 3rd order filters of [5], such a procedure is not desirable for higher order ones, especially if needed in high volume production. Rather, an iterative, easily programmable, automated tuning methodology is desired.

The automated tuning protocol used here seeks to maximize the energy in the filter response by maximizing the integrated area under the response spectrum. Specifically, the protocol for tuning is as follows:

1) Apply a white input signal, i.e., with constant power density at all frequencies around the passband, to the filter input and measure the total energy passed. This energy will be the total integrated energy under the filter frequency response spectrum.
2) Increment a single resonator's tuning voltage $V_{T,i}$ by a small amount in one direction, then measure the total integrated energy under the frequency characteristic.
3) If the energy decreased, then change the direction of the next increment for that same resonator. If it increased, then make the next increment in the same direction.
4) Continue adjusting $V_{T,i}$ and measuring energy output in steps until the energy output is maximized. At this point, the (integrated) area under the frequency characteristic is maximized.
5) Repeat steps 2 through 4 for each tuning voltage on each resonator and iterate the entire process as needed.

The above procedure assumes a convenient method for measuring the energy output, which can be done easily using diode-based circuitry. Alternatively, for the purposes of studying the progression of this tuning approach with the number of tuning increments, a network analyzer might be used to plot out and track the filter frequency characteristic while also integrating the total area under the curve to determine the direction of next tune. This, in fact, is what is done to verify this approach in Section IV.

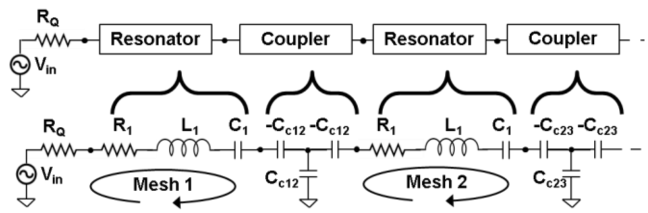

Fig. 5: Equivalent lumped element model for an *n*-th order coupled resonator filter indicating the meshes that must resonate at the geometric center frequency.

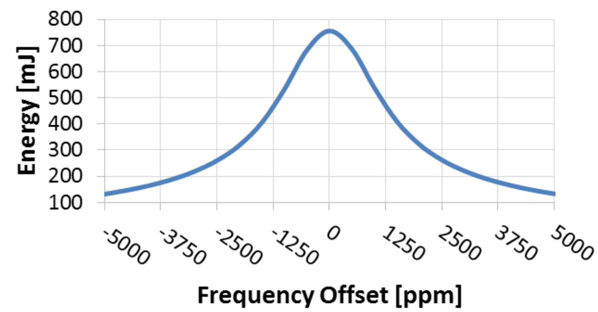

Fig. 6: Simulated 4-resonator filter output energy plotted against the frequency offset of a single one of its constituent resonators, assuming all other resonators are spot on.

A. Rationale Behind the Protocol

That the area under the frequency characteristic is maximized when the filter response is as designed is simply a consequence of the filter design procedure. After all, minimizing passband loss, i.e., maximizing passband energy, is one of the aims of filter design. That mere tuning of the constituent resonator frequencies can effectively correct the passband of a filter follows readily from mesh analysis of the filter's lumped equivalent circuit model shown in Fig. 5. Here the use of λ/4 coupling beams, as prescribed in [6], cancels the reactance of the coupling links to either side of a given resonator mesh, leaving only the effective *LCR* of the resonator itself in any given mesh. Since each such mesh must resonate at the geometric center frequency of the filter, this means that the core resonator in a mesh, i.e., the comb-transduced folded-beam resonator itself, must resonate at this frequency. Thus, tuning each of the resonators making up a filter so that all resonate at its geometric center frequency will correct a misshapen passband.

If the tuning protocol, however, required that individual resonator resonances be measured, this would make for a tedious tuning procedure. Fortunately, one need not monitor each resonator's frequency; rather, only the total energy passed by the filter with a white input signal need be measured—something easily done using a diode-based energy detection circuit. This works, since again, the area under the frequency characteristic is maximized when all meshes resonate at the geometric center frequency of the filter.

That a given tune step is in the right direction if it increases the filter output response to a white input obviously also follows from the above arguments. To further illustrate,

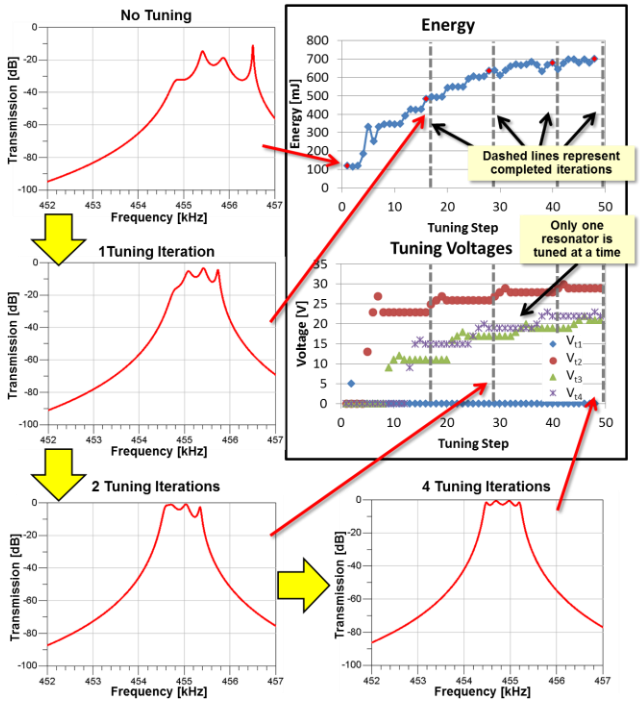

Fig. 7: Simulation demonstrating the method and efficacy of the energy maximizing tuning protocol.

Fig. 6 presents a plot of integrated energy passed by a 4-resonator Chebyshev filter as a function of the frequency deviation of one mismatched resonator from the filter's geometric center frequency, with all other resonators matched correctly. Here, the energy curve peaks only when the resonator's frequency matches the geometric center frequency.

B. Simulated Passband Correction

Analytical verification of this energy maximization-based protocol is perhaps best done via brute force simulation. To this end, Fig. 7 plots the integrated energy under a 400Hz-bandwidth 455kHz 4-resonator bandpass filter characteristic over a 5-kHz window around the filter center frequency as tuning increments are applied. Here, at the start, each resonator in the filter takes on a random mass error deviating between 200-4000ppm away from the designed value resulting in a severely distorted passband. As seen in Fig. 7, tuning voltage steps applied individually to each resonator following the protocol of Section III generate a change in the energy in the 5-kHz band, and this energy increases as each resonator is tuned in sequence. After iterating the tuning protocol through each of the four resonators, the filter response spectrum transforms from a practically unusable response to that of a near-perfect 4th order Chebyshev filter. The completion of four tuning iterations required a mere 49 individual voltage steps, which could be applied in rapid succession with a digital control system yielding almost instantaneous passband correction.

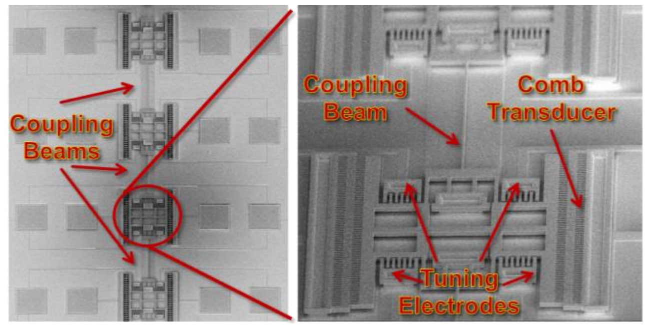

Fig. 8: SEM images of a micromechanical filter comprised of 4 coupled resonators alongside an enlarged view of one of its constituent capacitive comb-transduced resonators.

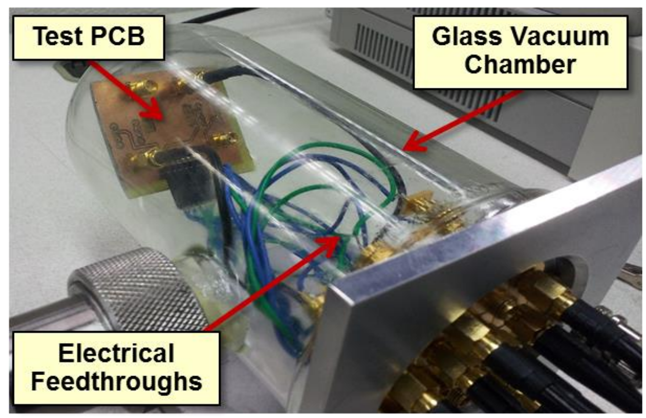

Fig. 9: Custom-made glass vacuum chamber used to test the filter tuning protocol of this work.

IV. Experimental Confirmation

Pursuant to demonstrating the described passband tuning protocol, 4-resonator filters using the topology of Fig. 1 were designed and fabricated using a three-mask polysilicon surface-micromachining process similar to that of [7]. Fig. 8 presents the SEM of one such filter, this one centered at 523.5kHz with a 532 Hz bandwidth, which is 0.1%.

Fig. 9 presents a photo of the test apparatus used to evaluate the tuning protocol of Section III, which included a custom-built glass vacuum chamber to provide a 10μTorr environment during measurement while also facilitating electrical connection to outside instrumentation via bias and signal feedthroughs. Since the intent of measurement was to study the progression of the filter frequency response as tuning was applied according to the protocol, an Agilent 8751A network analyzer, rather than an energy-sensing diode circuit, was used to collect data.

Fig. 10 presents three filter response spectra measured while tuning a fabricated 4-resonator 523.5-kHz filter. The response in (a), taken before any tuning, is clearly distorted, looking nothing like the desired passband response. After tuning resonator 1 via the described protocol, the spectrum of (b) results, which now looks much more like a bandpass filter response, except with considerable passband distortion. Finally, (c) presents the filter response after tuning is finished (i.e., after all resonators are tuned to maximize the integrated

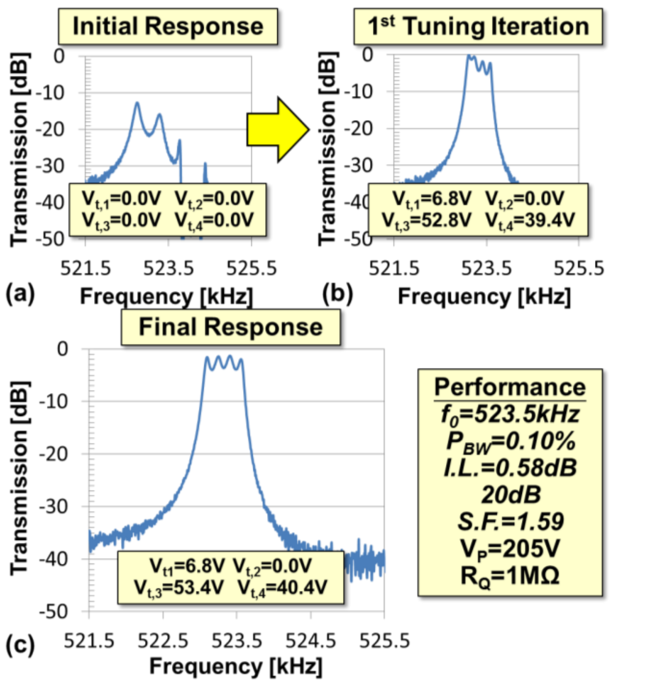

Fig. 10: Measured 4-resonator filter characteristic with (a) no tuning applied, i.e., straight out of the fab, (b) tuning voltages governed by one procedural iteration (through one of the constituent resonators), and (c) the final tuned response after two iterations.

output energy), showing the desired 0.1% bandwidth response with a 20-dB shape factor of just 1.59 (enabled by the use of four resonators) and an insertion loss of only 1.27dB, which is impressive for this small a percent bandwidth. Again, it is tuning, together with high constituent resonator Q's on the order of 25,000 (*cf*. Fig. 11), that makes possible this performance. Given that the filter response immediately after fabrication in Fig. 10(a) is quite bad, tuning in fact appears instrumental to achieving reasonable performance with this small a percent bandwidth.

It should be noted that the filter passband, although nice and uniform, exhibits about 3.4dB of ripple, which is 2.9dB more than the expected 0.5dB from design. This ripple is not a deficiency of the tuning protocol, but rather a consequence of insufficient electromechanical coupling, where the (C_x/C_o) of 6.3% for the measured filter is smaller than the 9.4% needed to attain a response with the designed ripple. The corrected passband in Fig. 10(c) is in fact as it should be with this consideration.

V. Conclusions

The demonstration of tuned passband correction capable of attaining a near perfect frequency response for a 523.5-kHz 0.1%-bandwidth 4-resonator micromechanical filter with only 0.58dB of insertion loss, a shape factor of 1.59, and passband ripple less than 3.5dB, confirms the energy maximization-based tuning protocol described herein. It should be noted that the tuning procedure demonstrated here utilizes a purely mathematical optimization and can therefore be driven

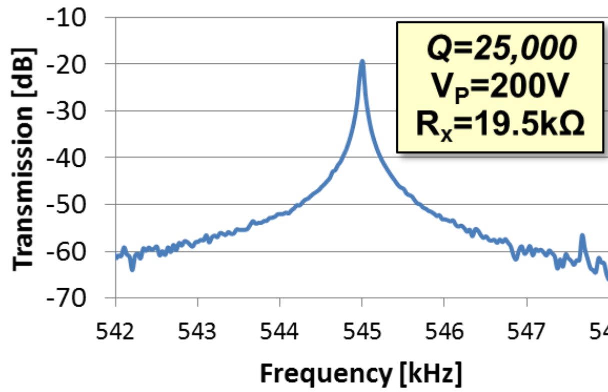

Fig. 11: Measured transconductance spectra for a single capacitive comb-transduced resonator

entirely by computer. Although this work demonstrated tuning via voltage-controlled electrical stiffness, any method for tuning or trimming is usable, including laser trimming [8] and localized anneal based methods [9]. The protocol is not limited to comb-driven resonator based filters, but rather practically any filter using tunable or trimmable resonators, including high-frequency disk resonators, which are next on the bucket list.

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