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MECHANICALLY CORNER-COUPLED SQUARE MICRORESONATOR ARRAY FOR REDUCED SERIES MOTIONAL RESISTANCE

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ABSTRACT

Substantial reductions in vibrating micromechanical resonator series motional resistance R_x have been attained by mechanically coupling and exciting a parallel array of corner-coupled polysilicon square plate resonators. Using this technique with five resonators, an effective R_x of 4.4kΩ has been attained at 64 MHz, which is more than 4.8X smaller than the 21.3 kΩ exhibited by a stand-alone transverse-mode square resonator, and all this achieved while still maintaining an effective Q >9,000. This method for R_x-reduction is superior to methods based on brute force scaling of electrode-to-resonator gaps or DC-bias increases, because it allows a reduction in R_x without sacrificing linearity, and thereby breaks the R_x versus dynamic range trade-off often seen when scaling.

Keywords: array, impedance, mechanical coupling, quality factor

I. INTRODUCTION

Having recently broken the GHz frequency "barrier" with Q's >1,500 in both vacuum and air [1], vibrating micromechanical ("µmechanical") resonators are emerging as viable candidates for on-chip versions of the high-Q resonators (e.g, quartz crystals, SAW's) used in wireless communication systems for frequency generation and filtering, with only a handful of issues left to solve [2]. Among the more important of the remaining issues that still hinder deployment of these devices in RF front ends is their larger-than-conventional impedance. In particular, it is their large impedance (i.e., motional resistance R_x) that presently prevents vibrating micromechanical resonator devices in the VHF and UHF ranges from directly coupling to antennas in wireless communication applications, where matching impedances in the range of 50Ω and 330Ω are often required.

Among the most direct methods for lowering the motional resistance R_x of capacitively transduced micromechanical resonators are (1) scaling down the electrode-to-resonator gap [3]; (2) raising the dc-bias voltage; and (3) summing together the outputs of an array of identical resonators. Unfortunately, each of these methods comes with drawbacks. In particular, although the first two are very effective in lowering R_x, with exponential dependences, they do so at the cost of linearity [4]. On the other hand, method (3) actually improves linearity while lowering R_x. Unfortunately, as will be described, method (3) is difficult to implement, since it requires resonators with precisely identical responses—a tough bill when Q's are as large as exhibited by micromechanical resonators.

This paper presents a method for lowering motional resistance based on method (3), with all of its linearity advantages, but dispensing with the need to match the responses of high-Q resonators by mechanically coupling them (as in Fig. 1) so that they automatically generate a single resonance response (i.e., mode) where all resonators vibrate at precisely the same frequency. Using this technique with five strategically-designed, corner-coupled square resonators (demonstrated for the first time), an effective R_x of 4.4kΩ has been attained at 64 MHz, which is more than 4.8X smaller than the 21.3kΩ exhibited by a stand-alone transverse-mode square resonator, and all this achieved while still maintaining an effective Q >9,000. This method for R_x-reduction is superior to methods based on scaling of electrode-to-resonator gaps or dc-bias increases, because it allows a reduction in R_x without sacrificing linearity [4], and thereby breaks the R_x versus dynamic range trade-off associated with "brute force" scaling.

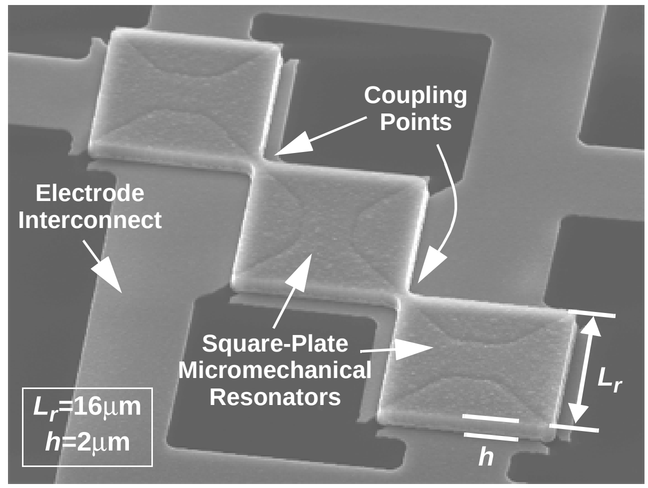

Fig. 1: SEM of a 64 MHz mechanically-coupled array of three square plate resonators.

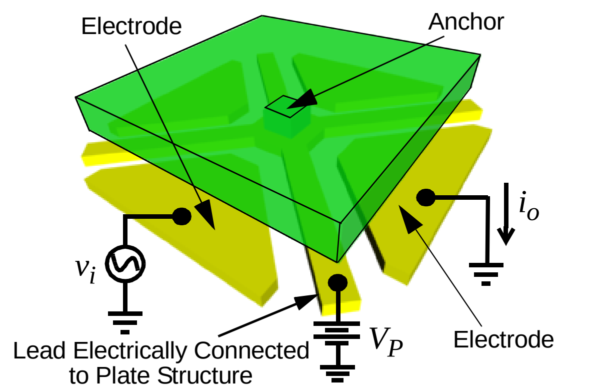

Fig. 2: Perspective-view schematic of a square plate µresonator in a two-port bias and excitation configuration.

II. SQUARE PLATE MICRORESONATOR

Pursuant to realizing reductions in R_x via mechanically-coupled parallel resonator arrays, a new transverse-mode square plate resonator, shown in Fig. 2, was strategically

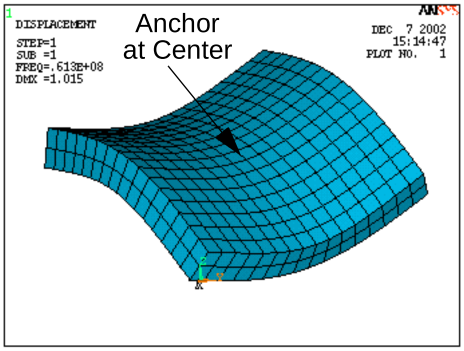

Fig. 3: The transverse-mode vibration mode shape of a square plate simulated via ANSYS.

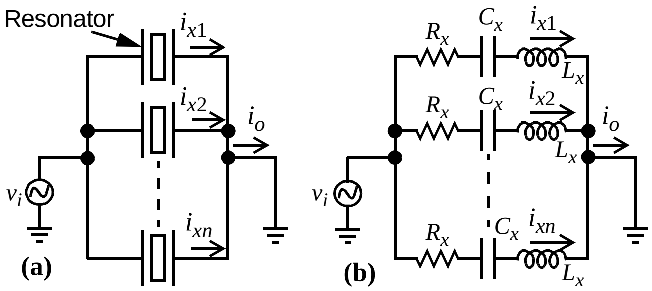

Fig. 4: (a) Array of resonators in parallel each with motional resistance R_x and its (b) equivalent RLC circuit, where n is the number of resonators in the array.

designed to allow for greater flexibility in the relative phasings between input and output signals during operation—something that will be needed to specify the array output frequency. The device consists of a square plate suspended 1800Å above four triangular capacitive transducer electrodes, with an anchor at its center. The electrodes are independently accessible (for phase flexibility) and identical in size for symmetry in electrostatic force distribution and topography. They are centered at anti-node locations for maximum effectiveness, and are separated by diagonal leads that pass through the anchor and provide an electrical connection to the plate. As seen in the ANSYS-simulated symmetric transverse-mode shape for this device in Fig. 3, the anchor at the center of the square is located at an effective motionless node point, at which vertical energy losses to the substrate are minimized due to momentum cancellation in the bulk of the device, resulting in higher Q for this device, hence, better stand-alone R_x than a clamped-clamped beam.

The resonance frequency f_o for a square plate vibrating in the mode of Fig 3 is given by [5]

$$f_o = \frac{20.56}{2\pi}\frac{h}{L_r^2}\sqrt{\frac{E}{12\rho(1-\nu^2)}} \qquad (1)$$

where h is the thickness of the plate, L_r is length of one of its sides, and E, ρ, and ν are the Young's modulus, density, and Poisson ratio, respectively, of its structural material.

III. COUPLED MICRORESONATOR ARRAY

Again, the basic method for lowering motional resistance R_x in this work entails the summing of currents from several resonators to produce a larger total current. Figure 4 presents schematics depicting an electrically-connected version of such an approach, where n resonators with identical frequency responses are connected in parallel and driven by a common

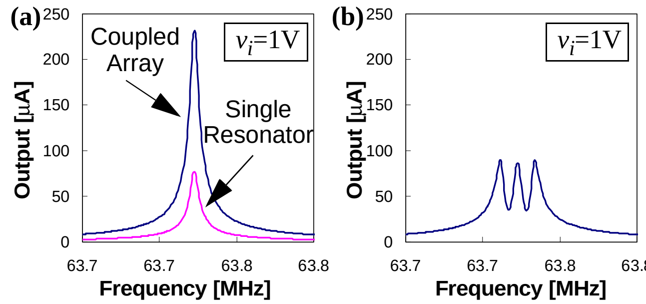

Fig. 5: Simulated frequency spectra showing (a) the increase in output attained by electrically coupling three square resonators; and (b) the effect of 0.01% mismatch resonator frequencies.

input source v_i, with their motional currents summed by wired connections. In the ideal case, where all n resonators are held to exactly the same resonance frequency, this method can work well to increase the total current i_o through the resonator array by n times for the same input voltage v_i, hence lowering the effective motional resistance R_x by the same factor n. In equation form, assuming identical resonators, the equivalent motional resistance of the array is given by

$$R_{x_{ARRAY}} = \frac{v_i}{i_o} = \frac{v_i}{n i_{x1}} = \frac{R_x}{n}. \qquad (2)$$

Figure 5(a) illustrates the increase in peak height attained when the outputs of three resonators, each with Q's of 20,000, are combined in this fashion. Unfortunately, this result is obtained only with the utmost control to match resonance frequencies, and even a tiny deviation in frequency from a matched case can dramatically compromise the combined output, as illustrated in Fig. 5(b), where resonator frequencies are mismatched by a mere 0.01%. Evidently, successful implementation of summation-based R_x-lowering in this electrically-connected fashion ultimately requires spacious and power hungry feedback control electronics to insure that the resonance frequencies of all resonators remain identical. Needless to say, this is not practical in scenarios where large numbers of resonators are needed in portable applications, such as in RF channel-select receiver architectures [2].

Fortunately, mechanical coupling offers a superior solution to this resonator matching problem. In particular, by coupling the n resonators mechanically, as shown for square plate resonators in Fig. 6, a mechanical filter structure is achieved, which now exhibits n modal frequencies, where each mode corresponds to a specific frequency and mode shape, as illustrated in Fig. 7 [6]. When the overall filter structure vibrates at a given modal frequency, *all* coupled resonators vibrate at this same frequency—a very convenient phenomenon considering the problem at hand! Obtaining the desired single resonator response then amounts to designing the mechanically-coupled resonator array system such that one of its modes is emphasized, while all others are suppressed.

Given this goal, it is advantageous to first separate the modes as far apart as possible. Since the bandwidth of a mechanical filter is proportional to the stiffness of its resonator-to-resonator coupling springs [3][6], the first step in selecting a single mode, while suppressing others, is to couple the resonators with very stiff springs. (This in sharp contrast to the the requirement for small percent bandwidth mechanical filters, which normally require fairly compliant springs.) Stiff mechanical coupling is achieved in Fig. 6 by coupling the

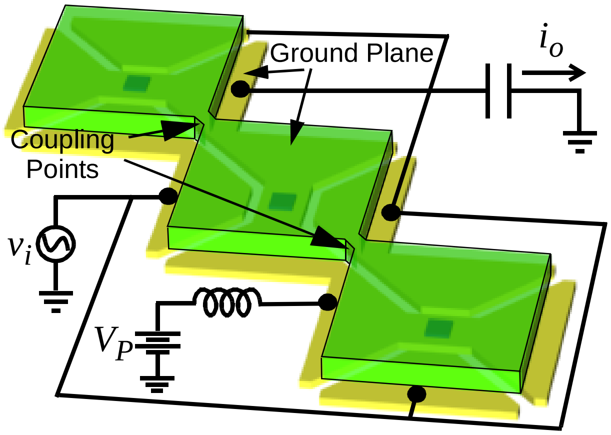

Fig. 6: Mechanically coupled array of three square resonators in a bias and excitation configuration that specifically selects the first filter mode. Note that the ground plane connects to all structures and is used for the output.

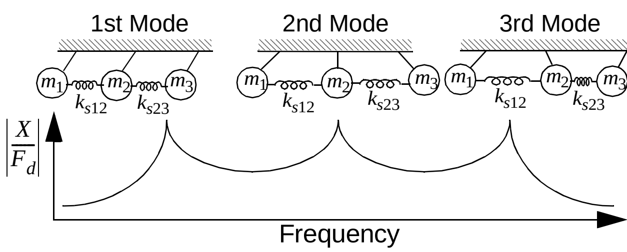

Fig. 7: Frequency spectrum showing the amplitude and phase of each mode for a mechanically coupled array of *n* resonators.

square resonators right at their corners via short, stiff stubs.

Pursuant to accentuating one mode, while suppressing others, Fig. 7 shows that each mode in a given filter is distinguished from another by the relative phasings between its resonators. Thus, unwanted filter modes can be suppressed by imposing properly phased ac forces on constituent resonators that emphasize phasings associated with a desired mode shape, while counteracting all others. In this regard, the phase flexibility by which the constituent resonators in a mechanically-coupled resonator array can be driven and sensed is key to selecting a single mode, and the availability of four different electrodes underneath the square resonators used for this work greatly facilitates the selection of a single mode. The input voltage connections shown in Fig. 6 are in fact chosen to accentuate the lowest frequency mode.

To illustrate the manner by which properly phased forcing signals can accentuate the lowest mode, while suppressing all others, Fig. 8 places the force distribution generated by the electrode hookup of Fig. 6 over ANSYS simulations of the shapes of each of the three modes. Note how the force directions F_d imposed by the electrode connection of Fig. 6 all go in the same direction as the mode shape displacements for the 1st mode. Note also how this same force configuration opposes at least one of the mode shape displacements for each of the other modes, resulting in their suppression.

Figure 9 presents SPICE simulated spectra for the equivalent *RLC* circuit of the coupled structure of Fig. 6 for two cases: (1) the structure operated as a mechanical filter, with v_i applied to one end resonator, and i_o taken at the other end; and (2) the structure operated as a parallel resonator array, using the hookup of Fig. 6. Note how effectively the parallel array raises the output current at the single desired lowest mode frequency, by more than 9dB.

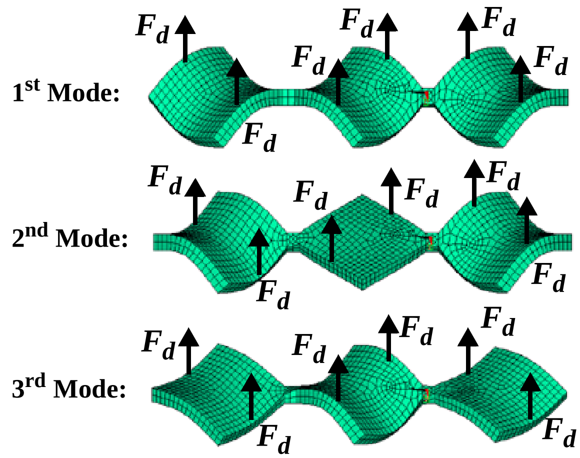

Fig. 8: ANSYS simulated filter mode shapes for the coupled three-resonator array of Fig. 6, with magnitude and directions for the electrostatic drive forces F_d induced by the hookup in Fig. 6.

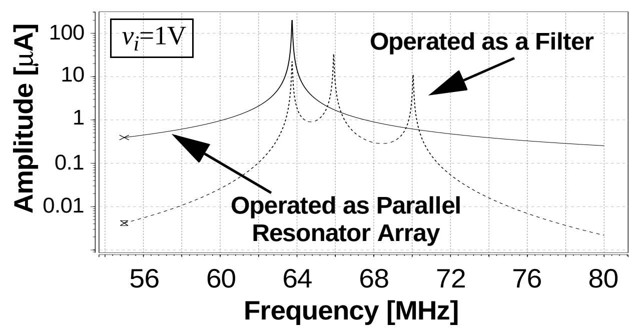

Fig. 9: SPICE simulated spectra for the structure of Fig 6 when operated as a mechanical filter and a parallel resonator array.

Table I: 64-MHz Square Plate Resonator Design

Design Parameters	Value	Unit
Resonance Frequency, f_o	64	MHz
Square Plate Side Length, L_r	16	µm
Plate thickness, h	2	µm
Electrode-to-Resonator Gap, d_o	1800	Å
Electrode Area, A_e	45	μm^2

IV. EXPERIMENTAL RESULTS

Stand-alone micromechanical square plate resonators and arrays of mechanically-coupled ones with resonance frequencies around 64 MHz were designed and fabricated in $POCl_3$-doped polysilicon using a small-gap surface-micromachining process similar to a previously reported version [3]. The constituent resonators of the coupled arrays were designed identically to stand-alone resonators in all dimensions, including electrode areas, to allow an accurate comparison of motional resistances. Table I summarizes the design used for 64-MHz square plates. Figures 10 and 1 present SEM's of a fabricated 64 MHz single square resonator and a mechanically-coupled array of three of them, respectively.

Figure 11 presents frequency characteristics measured under 200µTorr vacuum for a stand-alone device, and three- and five-resonator coupled array devices, all with Q's greater than 9,000, and with peak heights clearly increasing with the number of resonators coupled. To allow for direct comparison

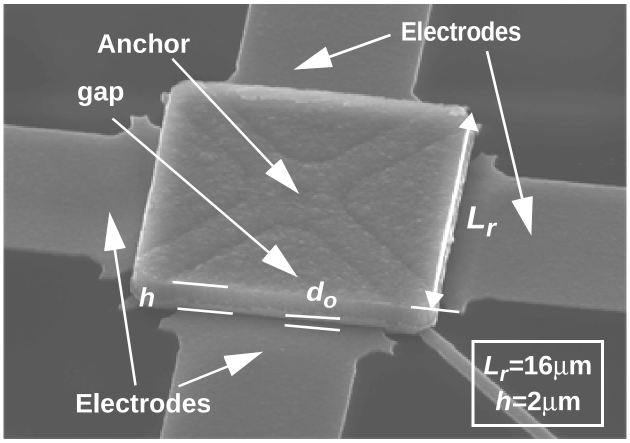

Fig. 10: SEM of a 64 MHz square plate µmechanical resonator.

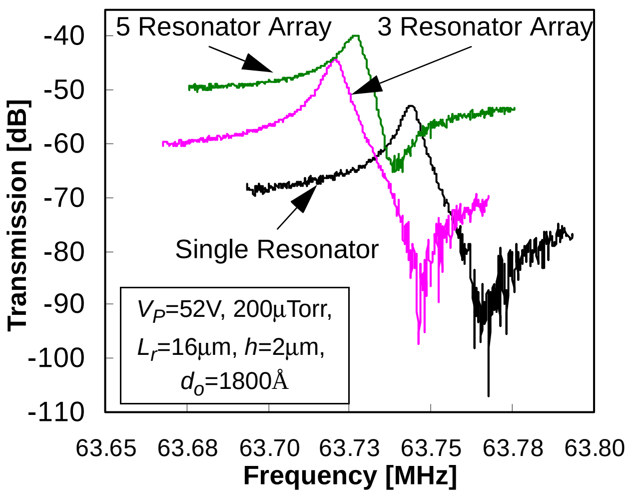

Fig. 11: Frequency response spectra for a 64 MHz stand-alone resonator and coupled square resonator arrays with three and five resonators.

Table II: 64-MHz Square Resonator Array Performance

No. of Resonators	Measured R_x [kΩ]	R_x Reduction Factor	Measured Q
1	21.3	1X	12,100
3	7.7	2.8X	10,900
5	4.4	4.8X	9,400

of motional resistances, the same DC bias was applied to each device for measurement, and a low AC drive level was used to avoid nonlinearity. Table II presents a comparison of R_x values for each of these devices, clearly showing decreases in R_x with increases in the number of resonators used. The R_x reduction factors of 2.8X and 4.8X exhibited by three- and five-resonator mechanically-coupled resonator arrays, respectively, verify the equivalence between reduction factor and number of resonators predicted by (2). Note that the decrease in the Q seen in Table II as the number of resonators in the array increases is partly responsible for R_x reduction factors that are not exactly equal to the number of resonators.

As seen in Fig. 11, in addition to lowering R_x, mechanical coupling of resonators also shifts the center frequency of the peak. Although such frequency shifts can be fixed by merely adjusting the applied dc-bias voltage V_P to constituent resonators, the design of the overall filter can also be adjusted to attain the right frequency, and this would be the preferred method.

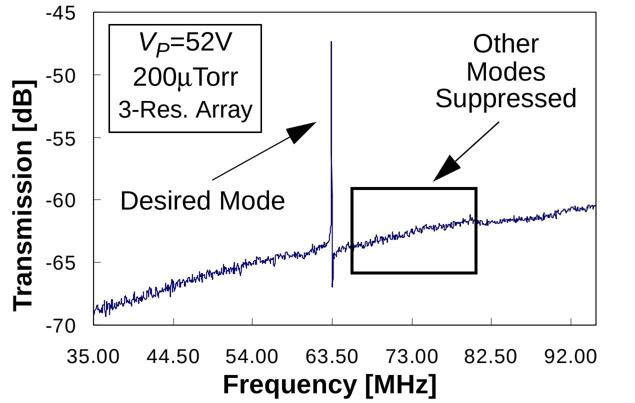

Fig. 12: Measured frequency spectrum verifying suppression of the higher frequency filter modes by choice electrode excitation.

Finally, to ascertain how effectively the unwanted modes in the mechanically coupled array have been suppressed, Fig. 12 presents the spectrum for the coupled square resonator array of Fig. 1 measured over a wide frequency range. The existence of only a single peak verifies that only the first filter mode is excited, while the second and third modes expected at 65.8 MHz and 70.0 MHz, respectively (as determined by ANSYS), have been effectively suppressed.

V. CONCLUSIONS

Mechanically-coupled parallel resonator arrays with combined output currents have been demonstrated with series motional resistances smaller than that of a single resonator by a factor equal to the number of resonators used in the array. The method demonstrated is also superior to mere combining of responses from separate resonators, since by mechanically coupling resonators, it automatically generates a single resonance response (i.e., mode) from all resonators, without the need for absolute matching of individual resonator responses. Although this paper has focused mainly on lowering resonator impedances, another direct benefit of this approach is a substantial enhancement of the power handling capability and linearity of the combined device. As such, this technique solves many of the remaining issues that presently slow the insertion of vibrating micromechanical resonator devices into practical communication systems, and thus, clears a path towards the fully integrated communication systems targeted by vibrating RF MEMS technology.

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