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DISK-ARRAY DESIGN FOR SUPPRESSION OF UNWANTED MODES IN MICROMECHANICAL COMPOSITE-ARRAY FILTERS

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ABSTRACT

A disk composite-array structure has been demonstrated that places its constituent disks in a triangular pattern around a "mechanical output" disk, while coupling them with half-wavelength links, in order to accentuate a desired resonant mode while suppressing unwanted modes. Using this mechanical circuit structure, disk array-composite filters with less than 0.2% bandwidth and centered in the 150-600 MHz UHF range have been demonstrated with no spurious modes in a ±200 MHz range around their radial-mode center frequencies. In addition to resonator arraying, these filters utilize lateral solid dielectric capacitive transducers to further reduce dc-bias voltages to as low as 4V. By replacing transverse resonators with higher frequency, higher Q lateral disks, this work provides a path to better performing communication oscillators and filters based on MEMS technology.

1. INTRODUCTION

With their tiny size, high on-chip integration density, Q's in the thousands from 10-2000 MHz [1]-[4], thermal stabilities on par with quartz [5], and stable aging characteristics [6], vibrating micromechanical circuits have emerged as an attractive approach for frequency generation and control in future wireless applications. To date, capacitively transduced micromechanical filters [1] and mixlers [7] have been demonstrated with impressive low loss frequency characteristics; however, their larger-than-conventional impedances have so far delayed deployment of these devices in conventional RF front ends. Recently, a coupled array approach that sums the outputs of numerous mechanically auto-matched resonators has been shown to lower the impedance of a 68.1-MHz square-plate resonator bandpass filter to the point of allowing L-network-aided matching to a 50 Ω termination, while also exhibiting less than 2.7 dB insertion loss (IL) for a 0.28% bandwidth [8]. The square-plate resonators used by this particular filter, however, are not easily scaleable to higher frequencies. Much higher frequency should be feasible if the array methods of [8] were applied using radial-mode disk resonators, which now regularly attain Q's >3,000 past 1 GHz [2]. Efforts to do so, however, would likely need to include enhanced strategies for suppressing spurious modes, which are more abundant in lateral-mode disks than the transverse square plates of [8].

This work harnesses the symmetry of radial-mode disks to suppress unwanted modes via both electrical and mechanical means. In particular, a disk composite-array structure has been demonstrated that places its constituent disks in a triangular pattern around a "mechanical output" disk, while coupling them with half-wavelength links, in order to accentuate a desired resonant mode while suppressing unwanted modes. When used to implement each constituent resonator in a bandpass micromechanical filter structure, this disk composite-array structure enables filter response spectra centered in the 150-600 MHz range with bandwidths less than 0.2%, impedances governed by the number of disks used, and no spurious modes within ±200 MHz. In addition to resonator arraying, these filters further utilize lateral solid-filled capacitive transducers (first described in [9]) to reduce dc-bias voltages down to as low as 4V and to significantly raise fabrication yields.

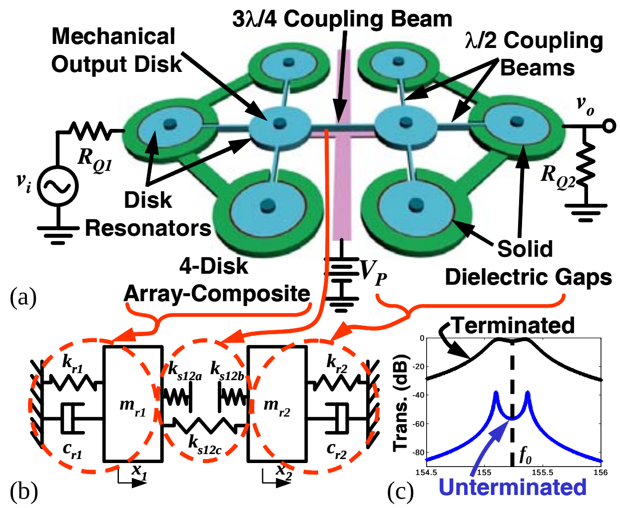

Fig. 1: (a) Perspective-view schematic, (b) equivalent mechanical model, and (c) terminated and unterminated frequency characteristics for a micromechanical disk-array filter in a typical two-port bias and excitation configuration.

2. DEVICE STRUCTURE AND OPERATION

Fig. 1(a) presents the perspective-view schematic of a micromechanical filter employing the disk array-composite resonators of this work, along with appropriate bias, excitation, and measurement hookups. As shown, this filter structure comprises two 4-disk resonator array-composites (to be described) linked by a single longitudinal mode coupling beam. When grouped into functional blocks, the whole structure mimics the lumped parameter mechanical system shown in Fig. 1(b), where a coupled two-resonator system generates

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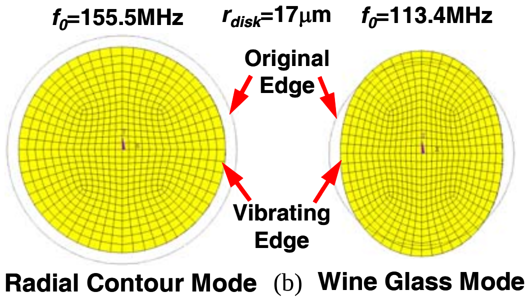

Fig. 2: Comparison of (a) the radial contour mode and (b) the wine-glass mode of a disk resonator.

two modes of vibration that then define the passband of an eventual filter response, shown in (c). The percent bandwidth of this filter response is governed by

$$P_{BW} = \frac{k_s}{k_r k_{12}} \quad (1)$$

where k_s is the coupling spring stiffness, k_r is the resonator stiffness at the attachment location, and k_{12} is the normalized coupling coefficient between resonator tanks for a given filter type (i.e., Butterworth, Chebyshev, etc.) [10]. According to (1), small percent bandwidths can be achieved only if the resonator stiffness can be made much larger than the coupler stiffness at the attachment location.

To insure good stability against process variations, the coupling beams of a micromechanical filter are generally designed so that their dimensions correspond to an odd multiple of a quarter-wavelength (λ/4) at the filter center frequency, in which case the mass and stiffness contributions from the coupler cancel one another at the attachment location to the adjacent resonators, allowing each resonator to be identical. (Without nλ/4 coupling, where n is an odd number, the resonators would need to differ from one another in order to achieve a symmetric filter passband.)

In general, coupled resonator structures like that of Fig. 1(b) will have at least as many potential vibration modes as the number of resonators coupled. For the structure of Fig. 1(a), this means there are 8 potential modes, and 6 of these modes will need to be suppressed if the filter characteristic of Fig. 1(c) is to be attained. To further complicate matters, the total structure will possess even more modes if the resonators being coupled are themselves multi-mode structures. This in fact is the case for the disks used in this work, which can vibrate in numerous modes, including the radial-contour and compound (2,1) (i.e., "wine-glass disk") modes shown in Fig. 2. In order to select the radial-contour mode, while suppressing the wine glass, the electrodes around input devices are made as fully concentric as possible, with openings only where coupling links are attached. This electrode geometry insures an electrostatic force contour that matches the shape of the radial-contour mode of Fig. 2(a), so accentuates it over the wine-glass or any other mode.

Although the use of near fully concentric electrodes practically insures that disks vibrate in the radial-contour mode, thereby preventing mode multiplication, it does nothing to suppress the 6 remaining unwanted modes of the structure of Fig. 1(a). Rather than outright suppress these 6, it is perhaps easier to just move them far out of the way. This can be accomplished by coupling them using springs with infinite stiffness, which would then move all modes an infinite frequency distance away from the remaining fundamental mode. An effectively infinite coupler stiffness can be achieved for frequencies close to the filter center frequency if the links coupling the disk resonators are given dimensions corresponding to an effective half-wavelength (i.e., λ/2) at the filter center frequency, or when their array coupling beam lengths satisfy

$$L_a = \frac{n \times \sqrt{E/\rho}}{2 f_0}, \quad n = 1,2,3... \quad (2)$$

where E and ρ are the Young's modulus and density, respectively, of the structural material, f_0 is the filter center frequency, and n is the integer. When designed according to (2), the coupling links effectively become rigid masses, with near infinite stiffness, at the filter center frequency. With rigid mass couplers, the 4-disk coupled-array effectively becomes a single "composite" resonator, with a single resonance frequency mode. Each 4-disk array of Fig. 1(a) then equates to a single mass-spring-damper in the circuit of Fig. 1(b), and the whole structure yields the frequency response of Fig. 1(c). Fig. 3 further conveys the mode shapes corresponding to each

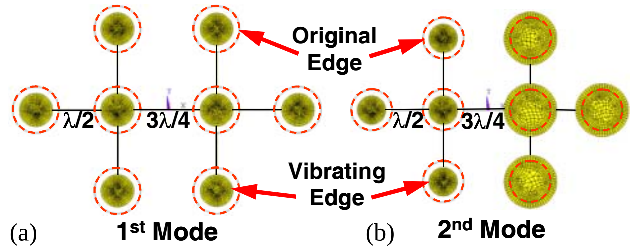

Fig. 3: Finite element simulated mode shapes for the micromechanical contour-mode disk-array filter of Fig. 1(a). (a) In-phase mode. (b) Out-of-phase mode.

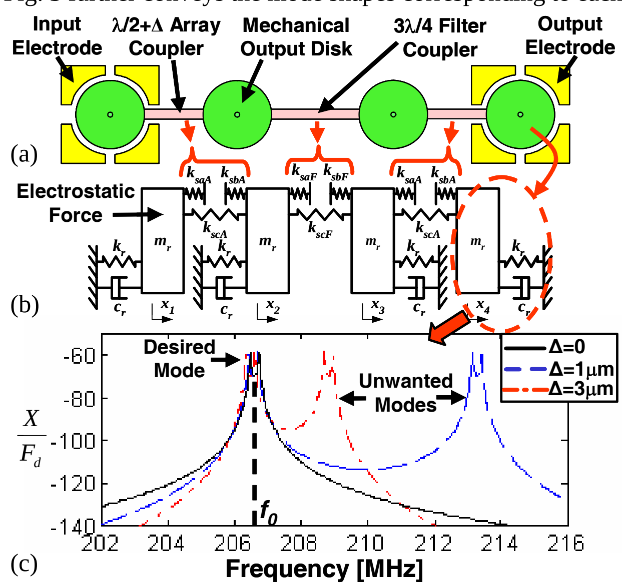

Fig. 4: (a) Schematic, (b) equivalent lumped parameter mechanical circuit, and (c) simulated frequency characteristics using the mechanical model of (b) for a simplified disk-array filter, where each resonator-array consists of only two disk resonators for convenience.

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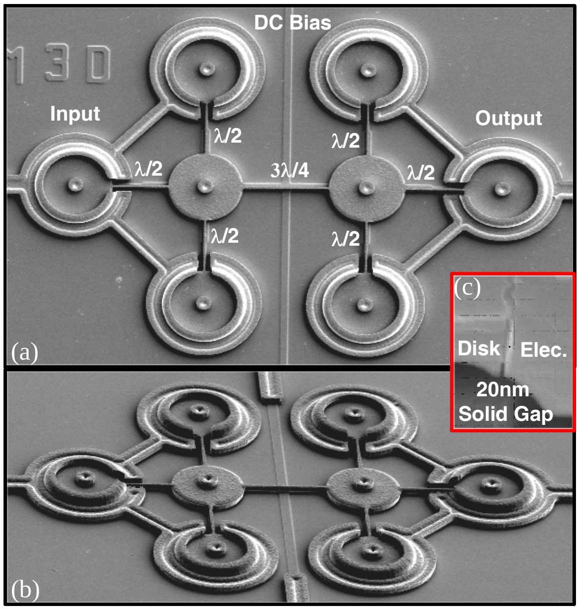

Fig. 5: (a) Top-view (155 MHz), (b) iso-view (207 MHz), and (c) gap-zoomed SEM’s of polysilicon fabricated micromechanical disk-array filters.

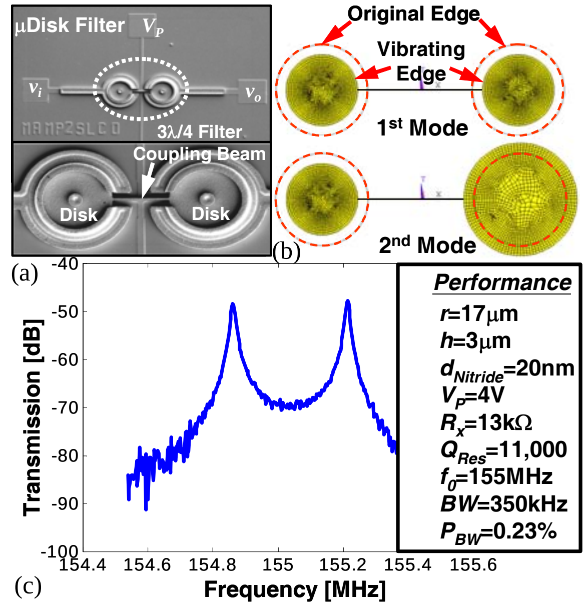

Fig. 6: Micromechanical contour-mode disk filter. (a) SEM and zoom-in. (b) Finite element simulated mode shapes. (c) Measured frequency characteristic under vacuum using a typical two-port measurement scheme.

peak of the filter response for the complete structure of Fig. 1(a), as simulated by finite element analysis.

The extent to which half-wavelength coupling can convert a disk array into a single “composite” resonator is governed by how exactly the dimensions of the coupling links correspond to λ/2. To illustrate, Fig. 4 presents simulations based on a 206-MHz filter structure using much simpler 2-disk array-composite resonators that show how a deviation from the needed λ/2 length of 19.4 μm by just Δ=1 μm (or 5.2%) leads to an unwanted mode less than 8 MHz away, and as the deviation grows, the unwanted mode moves ever closer to the desired filter passband. In particular, a 3 μm deviation places the unwanted mode only 2 MHz away. Clearly, precise coupling beam design is crucial for mode suppression.

As was the case for the square resonator arrays of [8], arraying of disks increases the effective stiffness seen at any point on any edge of any disk in the array by the number of disks used in the array. In equation terms [8]

$$k_{rA} = Nk_r \tag{3}$$

where k_r is the stiffness at the edge of a single disk resonator, and N is the number of disks in the array. From (1) and (3), it follows that the bandwidth of a given filter using array-composite resonators can be reduced simply by increasing N (i.e., by coupling more resonators into the array). In particular, the 4-disk array used in the filter structure of Fig. 1(a) should provide a 4X larger coupler attachment stiffness than if single resonators were used [8], which in turn should allow a 4X smaller bandwidth. In effect, arraying allows bandwidth reduction without the need for either (i) sub-μm coupling beam dimensions [1]; or (ii) low-velocity notch-coupling [11]. By circumventing the need for these dimension-dependent strategies, arraying greatly relaxes the fabrication tolerance required to achieve a given small bandwidth.

3. EXPERIMENTAL RESULTS

Fig. 5(a)-(b) presents SEM’s of the fabricated disk-array filters centered at 155 MHz and 207 MHz used to evaluate the methods described in Section 2. As in [9], the use of 20-nm solid nitride-filled gaps shown in Fig. 5(c) not only lowered the impedance of all filters, but also greatly improved the fabrication yield (to 100%) versus previous air-gap processes. Dies containing these filters were mounted on pc boards, which were then inserted into a custom vacuum chamber equipped with electrical feedthroughs to external measurement instrumentation for testing.

To more precisely delineate the location of modes, both wanted and unwanted, the filters of this paper were measured unterminated (i.e., without termination resistors, R_Q [1]). Although this measurement style hides the actual insertion loss of the filters, it is more suited to the main focus of this paper, which is to better understand the origin of unwanted modes and to evaluate strategies that suppress them.

For later comparison purposes, a 155-MHz filter using single disk resonators, shown in Fig. 6(a) along with its mode shapes in (b), was measured first under 20 μTorr vacuum. Fig. 6(c) presents the measured frequency characteristic for this filter, showing a bandwidth of 350 kHz (i.e., 0.23%). There were no spurious modes over a large frequency range around its passband.

The disk array-composite filters of Fig. 5 were then tested using the two-port test configuration shown in Fig. 1(a) with R_Q’s = 50 Ω. Fig. 7 presents their measured (unterminated) frequency characteristics, each using a dc-bias voltage of only 4V. The 155-MHz version achieves a bandwidth of 95 kHz (i.e., 0.06%), while the 207-MHz one achieves a 355-kHz bandwidth (i.e., 0.17%), and neither shows any spurious

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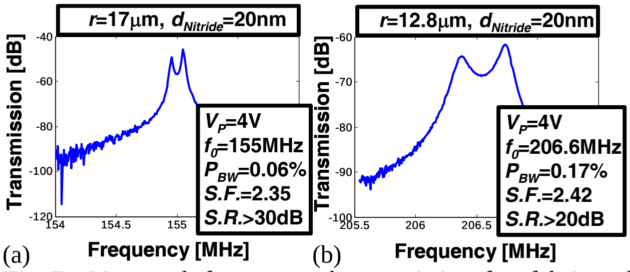

Fig. 7: Measured frequency characteristics for fabricated micromechanical disk-array filters centered at (a) 155 MHz and (b) 207 MHz, both with solid dielectric gaps of 20 nm.

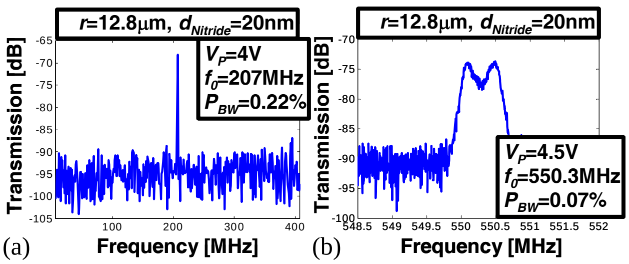

Fig. 8: Measured frequency characteristics for a fabricated micromechanical disk-array filter in its (a) 1st radial mode at 207 MHz in a 400 MHz wide scanning span with no spurious modes; and (b) 2nd radial mode at 550 MHz.

modes in the immediate vicinity of the passband. The measured bandwidth for the 155-MHz one is nearly 4X smaller than that of single-disk filter in Fig. 6(c), verifying that the stiffness of 4-disk array is 4X larger than that of a single disk, as predicted by the theory of Section 2.

Fig. 8(a) presents a wide-span frequency characteristic for the 207 MHz disk-array filter, again, without any spurious modes in a 400 MHz range. Fig. 8(b) presents the measured frequency characteristic for this 207-MHz disk-array filter in its 2nd radial mode, showing a center frequency of 550.3 MHz (i.e., UHF range) and a 0.07% bandwidth.

To investigate the degree to which triangular placement pattern of disks in the array of Fig. 1(a) suppresses unwanted modes, Fig. 9 presents the measured frequency characteristic

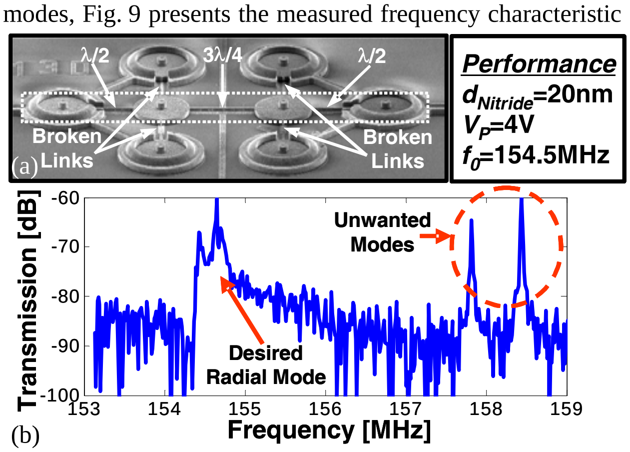

Fig. 9: (a) A fabricated micromechanical disk-array filter which purposely mimics the filter structure of Fig. 4(a). (b) Measured frequency characteristic showing unwanted modes when a triangular disk placement pattern is not used.

for a filter where links were physically removed (by breaking them) from the design of Fig. 1(a) to achieve the simpler array-composite disk placement of Fig. 4(a). Even though it utilizes half-wavelength coupling in its array-composite resonators, spurious modes are still seen that were not present when the full triangular disk placement is used. Although a more controlled experiment should be conducted to remove the influence of mass imbalances caused by left-over link breakages on disks, it seems that a triangular disk placement that couples along more axes into a receiving disk does help to reduce spurious modes.

4. CONCLUSIONS

Capacitively transduced micromechanical filters have been demonstrated that interlink radial mode disks using half-wavelength couplers in a triangular pattern around a "mechanical output" disk to accentuate a desired mode while suppressing all other nearby modes. Fully concentric electrodes were also shown to specify the radial-contour mode of the disks, while suppressing the wine-glass or other modes. Using these two mode-suppressing strategies, small percent bandwidth disk-array-composite filters centered in the 150-600 MHz range have been demonstrated with no spurious modes in a wide scanning span around their radial-mode center frequencies. These results now encourage even larger disk arrays that should allow tailored termination impedances in future RF channel-select filter banks targeted for future wireless communications circuits.

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