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Enhancement of Micromechanical Resonator Manufacturing Precision Via Mechanically-Coupled Arraying

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***Abstract*— A statistical comparison between the resonance frequency variations of stand-alone micromechanical disk resonators and mechanically-coupled array composites of them reveals that mechanically-coupled arraying of on-chip micromechanical resonators can very effectively enhance the manufacturing repeatability of resonance frequencies. In particular, twenty 3-disk resonator array-composites on a single die achieve a measured resonance frequency standard deviation as small as 165.7 ppm around a 61.25 MHz average, which is significantly smaller than the 316.4 ppm measured for twenty stand-alone disk resonators on the same die. This new standard deviation reduces the expected filter percent bandwidth achievable with a 90% confidence interval without the need for trimming from the 1.89% of previous work to now just 0.86%. Larger arrays should further reduce the frequency standard deviation, perhaps to the point of allowing trim-free RF channel-select bandwidths with reasonable manufacturing confidence interval.**

***Keywords*— MEMS, micromechanical filter, wireless communications, mechanical circuit, LSI, VLSI, RF MEMS, standard deviation.**

I. Introduction

Micromechanical filters constructed using high-Q on-chip micromechanical resonators have recently been demonstrated with insertion losses less than 2.5dB for filter percent bandwidths small enough to select individual communication receiver *channels* (as opposed to bands of channels), while rejecting all *out-of-channel* interferers. For example, the filter of [1] utilized micromechanical disk resonators with Q's of 10,000 to achieve a two-pole Chebyshev response with a percent bandwidth of 0.06%, for which only 2.43dB of insertion was observed. If implemented using the much higher frequency disks of [2], which also achieve Q's >10,000, such a filter structure might then allow channel-selection right at RF, immediately after the antenna in a wireless receiver. As described in [3], by removing all interferers and allowing only the desired signal to pass to subsequent electronics in the receive path, such an RF channelizer would greatly lower the dynamic range requirements of the electronics, and thereby substantially enhance the robustness and lower the power consumption of the receiver.

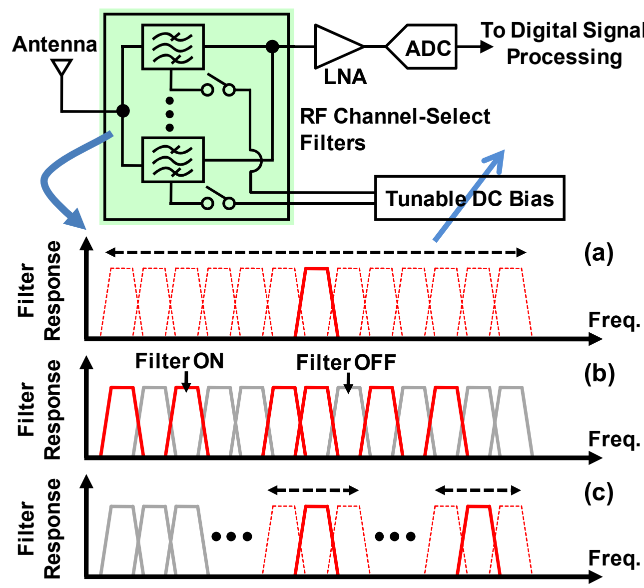

Fig. 1: Schematic of a channelizing RF front-end with three implementation options: (a) A single tunable channel-selecting filter. (b) A large bank of non-tunable, but on-off switchable, filters. (c) A smaller bank of tunable and on-off switchable filters.

To realize this, a practical RF channelizer would likely need to employ one of the following schemes:

1) A single channel-selecting RF filter tunable over the desired frequency range, as depicted in Fig. 1(a).
2) A bank of on-off switchable channel-selecting RF filters, placed side-by-side and covering the desired frequency range, as depicted in Fig. 1(b).
3) A combination of 1) and 2) above, i.e., a bank of tunable *and* on-off switchable channel-selecting RF filters covering the desired frequency range, as depicted in Fig. 1(c).

Much of the described work was supported by DARPA.

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Note that although approach 2) requires the largest number of resonators, it also can realize the fastest spectrum analyzer of the three approaches—something needed for future cognitive radio targets [4][5]. Also, note that each of the above schemes is possible using filters comprised of capacitively transduced micromechanical resonators, where the dc-bias required for resonator operation can be utilized to both switch a given filter on and off [6] and tune its center frequency [7][8].

Each of the above schemes also benefits greatly from its tunable or banked implementation, which very conveniently obviate the need for stringent absolute tolerances in center frequency. In particular, for the case of approaches 1) and 3), as long as the fabrication process can place a filter's center frequency within the band over which the filter must be tuned, the exact value of the untuned center frequency does not matter. For the case of the bank of filters in approach 2), it again does not matter where the filter initial center frequencies land immediately after fabrication, as long as the separations between the center frequencies of adjacent filters is correct, and as long as a global frequency tuning capability exists where all filters can be tuned in one direction simultaneously. As already mentioned, the dc-bias provides such a global frequency tuning capability.

Still, although the above schemes obviate the need for minimum absolute tolerances, they do not necessarily eliminate the need for matching tolerances. In particular, the flatness or accuracy of the passband of any filter relies heavily on the relative frequencies of its constituent resonators. Because of this, and because wafer-level fabrication processes often achieve much better matching tolerances than absolute tolerances, past micromechanical filters have been designed using identical resonators with quarter-wavelength couplers to spread their frequencies and generate a passband [9]. Here, the matching tolerance of the fabrication process used must be sufficiently good to avoid passband distortion caused by mismatches in the constituent resonators [10].

Unfortunately, although sufficient for 1.6% bandwidth filters [10], the matching tolerances achieved by a university microfabrication facility are still not good enough to achieve channel-selecting filters, with percent bandwidths below 0.14% at GHz frequencies. Tuning via dc-bias voltages can of course still be used to correct for mismatch-derived passband distortions, but this would entail more complicated control electronics and interconnect routing, so probably should be avoided, if possible. At any rate, a method for reducing the mismatch tolerances, i.e., frequency standard deviation, of a given micromechanical resonator is highly desirable.

Pursuant to attaining improved frequency standard deviations, this work employs mechanically-coupled array composite resonators [11] to effect a frequency averaging that reduces the overall standard deviation of frequency by approximately the square root of the number of resonators in the array. Specifically, a statistical comparison between the resonance frequency variations of stand-alone micromechanical disk resonators and mechanically-coupled array composites of them reveals that mechanical-coupled arraying of on-chip micromechanical resonators can very effectively enhance the manufacturing repeatability of resonance frequencies. In particular, twenty 3-disk resonator array-composites on a single die achieve a measured resonance frequency standard deviation as small as 165.7 ppm around 61.25 MHz, which is significantly smaller than the 316.4 ppm measured for twenty stand-alone disk resonators on the same die.

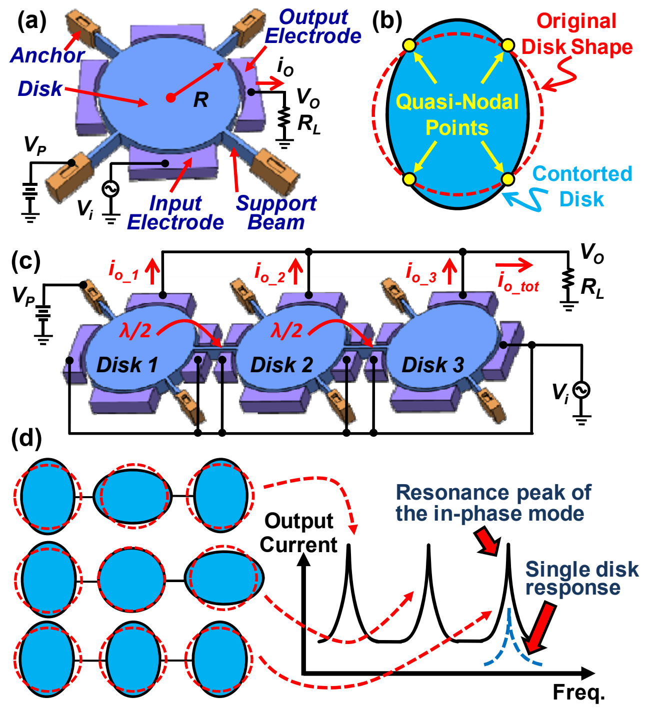

Fig. 2: (a) Perspective-view schematic of a stand-alone micromechanical wine-glass mode disk resonator in a typical two-port bias and excitation configuration and (b) schematic of its compound (2,1) mode shape. (c) Perspective-view schematic of a 3-disk composite array resonator and (d) its three different mode shapes.

II. TESTED DEVICES

Fig. 2(a) presents the basic micromechanical resonator used in this work as a vehicle to evaluate the efficacy of arraying for better repeatability. This device, dubbed the "wine-glass disk" resonator [12], consists of a polysilicon disk supported by four beams attached at quasi-nodal locations, and surrounded by two pairs of electrodes along two orthogonal axes. When driven by the combination of a dc-bias voltage applied to its structure and an ac voltage at its resonance frequency applied to one of the electrode pairs, the disk vibrates in the compound (2,1) mode shape, where it extends along one axis while contracting along the orthogonal axis, as depicted in Fig. 2(b). This figure also shows how the support beam attachment locations correspond to extensional nodal locations (but not tangential, hence the term "quasi-nodal"). In practice, these locations are not perfect extensional nodes, either. They, however, negate motion well enough that choosing them as support attachment locations minimizes energy loss through the supports to the substrate, thereby maximizing the Q of the compound (2,1) mode. As shown in Fig. 6, measured Q's regularly exceed 130,000.

With Q's this high, the stand-alone device of Fig. 2 is obviously quite useful as the frequency setting element for a

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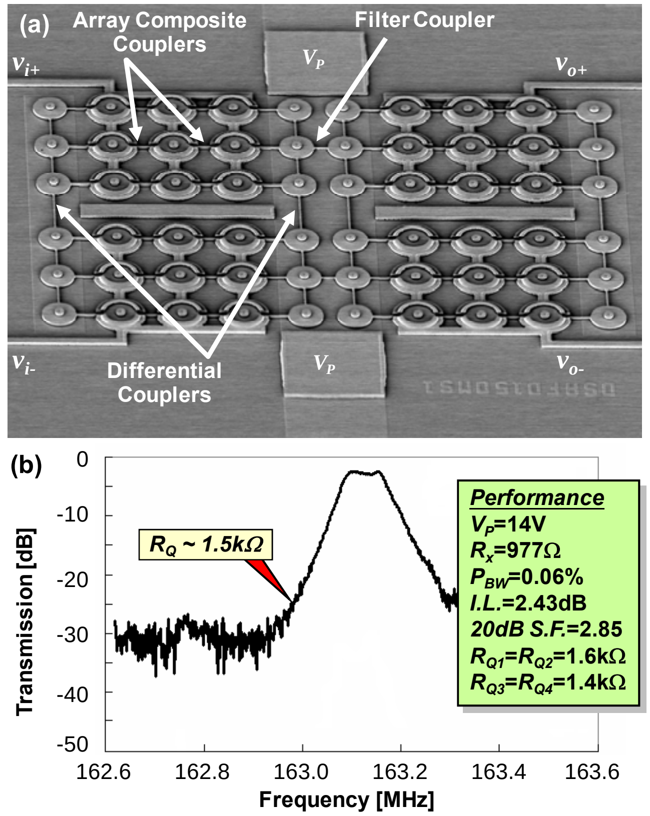

Fig. 3: (a) SEM photo of a 163-MHz differential disk-array composite micromechanical filter and (b) frequency transmission spectrum.

self-sustaining oscillator, and indeed oscillators that satisfy the reference oscillator phase noise specifications for GSM cellular phones have already been successfully achieved using stand-alone wine-glass disk resonators [12]. Still, improved device properties and much greater functionality ensue when a number of the above disk resonators are mechanically coupled into a composite array resonator, such as shown in Fig. 2(c). In past work, mechanically coupled arrays have been used to alleviate certain perceived micromechanical resonator deficiencies, specifically high impedance and low power handling ability relative to much larger conventional high-Q devices, such as quartz crystals. In the mechanically coupled array composite of Fig. 2(c), half-wavelength mechanical coupling between the resonators forces them to vibrate at the same mode frequency, which then allows their responses to directly add, into a much larger output current—larger by a factor equal to the number of resonators used in the array. This larger output current, of course, results in higher power handling and lower motional resistance, each by a factor equal to the number of resonators used. To insure a single resonance peak, the array composite resonator of Fig. 2(c) uses half-wavelength coupling and strategic phasing of electrode excitations to accentuate a desired mode while suppressing unwanted ones.

Among examples where such array composite resonators have been used successfully are the GSM-phase-noise compliant oscillator demonstrated in [13] that achieved phase noise marks of -140dBc/Hz at 1kHz offset from a 13-MHz carrier and -150dBc/Hz at far-from-carrier offsets; and the disk array composite filter of [1] that achieved an insertion loss of only 2.43dB for a 0.06% bandwidth centered around 163 MHz. The last of these, depicted in Fig. 3 with a measured transmission spectrum, is particularly compelling, as it actually employs four identical arrays in a hierarchical mechanical circuit structure. As described in [1], the four arrays not only enable termination impedances of 1.5kΩ that are optimal for a fully integrated receiver front-end, but also make possible a differential input/output configuration that suppresses electrical feedthrough and eliminates spurious mechanical responses. The resulting filter occupies only 560μm×360μm and, if translated to higher RF frequencies, would be much smaller while also suitable for implementation of the channelizers in Fig. 1.

Unfortunately, however, the filter response in Fig. 3(b) was achievable only via tuning of its resonator frequencies via the dc-bias-dependent electrical stiffness mentioned in Section I. Indeed, immediately after fabrication, mismatches between resonators in each array generate an offset in the relative positions of the two filter peaks, leading to a large dip in the ensuing filter passband, i.e., distorting the filter passband.

III. BENEFITS OF ARRAYING

Interestingly, if the filter of Fig. 3 had only used more resonators in its four array composites, it might have required much less tuning, if any at all. To see this, we first establish that for certain modes of a mechanically-coupled array, the frequency of the array at which all of its constituent resonators vibrate essentially ends up being the average of the resonance frequencies of each of the constituent resonators.

A. Resonance Frequency Averaging

The resonance frequency of the in-phase-mode of the 3-disk array composite depicted in Fig. 2 can be expressed by [11]

$$f_{array} = \frac{1}{2\pi}\sqrt{\frac{\sum_{i=1}^{3} k_i}{\sum_{i=1}^{3} m_i}} = \frac{1}{2\pi}\sqrt{\frac{k_1 + k_2 + k_3}{m_1 + m_2 + m_3}} \quad (1)$$

where k_i and m_i are the effective spring constant and mass, respectively, of the ith resonator. For the case where the resonators in the array are identically dimensioned wine-glass mode disks, (1) predicts that the in-phase mode frequency of the array will be the same as that of a single one of its constituent resonators.

If on the other hand each resonator experiences small deviations in frequency Δf_i, perhaps arising from small deviations in radius ΔR_i that in turn generate deviations in mass Δm_i, then (1) can be expanded as

$$\begin{aligned} f_{array} &= \frac{1}{2\pi}\sqrt{\frac{3k_0}{(m_0+\Delta m_1)+(m_0+\Delta m_2)+(m_0+\Delta m_3)}} \\ &= \frac{1}{2\pi}\sqrt{\frac{3k_0}{3m_0}}\cdot\left(1+\frac{1}{3}\frac{\Delta m_1}{m_0}+\frac{1}{3}\frac{\Delta m_2}{m_0}+\frac{1}{3}\frac{\Delta m_3}{m_0}\right)^{-1/2} \end{aligned} \quad (2)$$

where k_0 and m_0 are the designed effective spring constant

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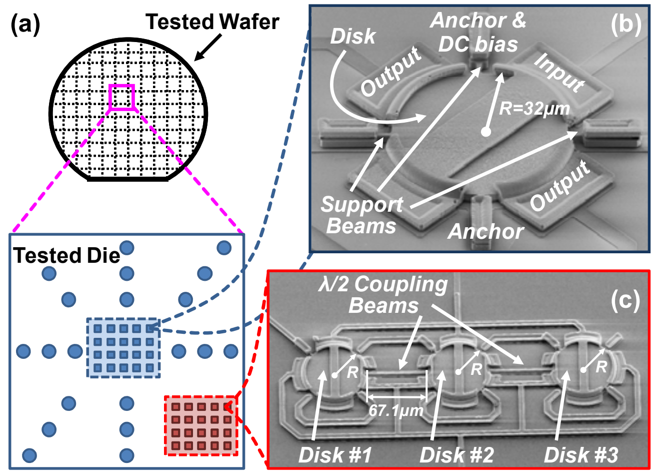

Fig. 4: (a) Relative locations on each tested die and SEM photos of the measured 61-MHz (b) stand-alone wine-glass mode resonators; and (c) 3-disk mechanically-coupled array composites. The disks of (b) and (c) all have radius R = 32 μm, thickness h = 3 μm, and electrode-to-resonator gap spacing d_o = 100 μm. In addition, the wavelength λ = 134.2 μm.

and mass, respectively, and where it has been recognized that the stiffness k_0 of a wine-glass disk resonator is to first order not a function of radius. If the deviations between resonators are small, (2) can be Taylor expanded to first order to yield

$$f_{array} = f_s \cdot \left[1 + \left(-\frac{1}{2}\right)\left(\frac{1}{3}\frac{\Delta m_1}{m_0} + \frac{1}{3}\frac{\Delta m_2}{m_0} + \frac{1}{3}\frac{\Delta m_3}{m_0}\right)\right] \quad (3)$$

which then reduces to

$$f_{array} = \frac{1}{3}(f_s - \Delta f_1) + \frac{1}{3}(f_s - \Delta f_2) + \frac{1}{3}(f_s - \Delta f_3)$$
$$f_{array} = \frac{1}{3}(f_1 + f_2 + f_3) \quad (4)$$

where f_s is the designed resonance frequency of single disk. Thus, for the case where all resonators are nearly identical, i.e., the deviations are small, the resonance frequency of an array composite of them is approximately equal to the average of the frequencies of its constituent resonators.

B. Reduction in Standard Deviation

The frequency averaging governed by (4) is beneficial, since it reduces the resonance frequency standard deviation of the array composite resonator caused by random process variations [14]. In particular, the standard deviation of the resonance frequency of a disk-array composite resonator is given by

$$\sigma_{f_{array}} = \frac{1}{N}\sqrt{\sum_{i=1}^{N} VAR(f_i) + \sum_{i,j=1,i\neq j}^{N} 2COV(f_i, f_j)} \quad (5)$$

where N is the number of resonators coupled in the array. In general, process variations across a wafer might not be completely random, so the covariance term in (5) would take on a finite value. However, for the present case of an array of resonators occupying a very small area on a die, the variations might indeed take on a more random nature, which would then null out the covariance terms, yielding a very simple expression for the composite array frequency standard deviation:

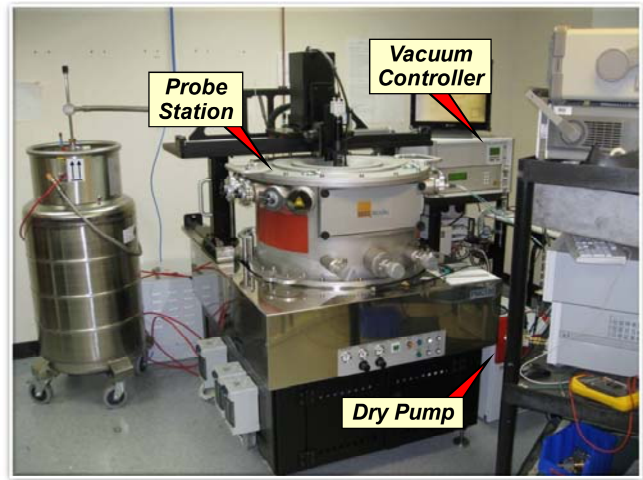

Fig. 5: Photo of the SUSS MicroTech PMC150 temperature-controllable vacuum probe station used to collect statistical resonance frequency data.

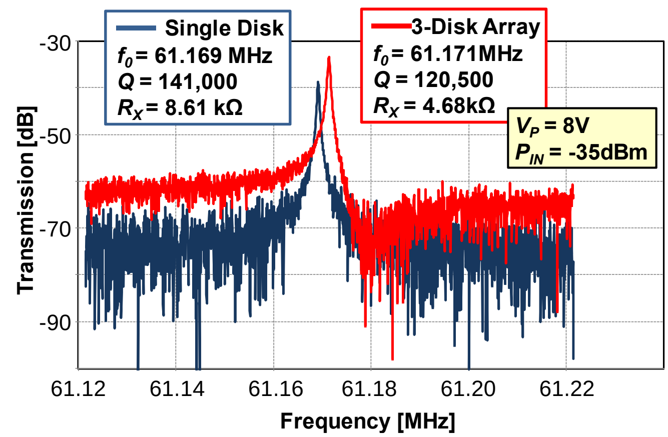

Fig. 6: Measured plots comparing the frequency characteristics of a stand-alone 61-MHz wine-glass mode micromechanical disk resonator (in blue) and a 3-disk array composite of them (in red).

$$\sigma_{f_{array}} = \frac{\sqrt{N}}{N}\sigma_{f_i} = \frac{1}{\sqrt{N}}\sigma_{f_i} (i = 1, 2, \cdots, N) \quad (6)$$

IV. EXPERIMENTAL RESULTS

To verify the above formulations, 61-MHz micromechanical wine-glass disks and three-resonator array composites of them were fabricated via the small lateral-gap polysilicon surface micromachining process described in [2].This work compiles measured data from five dies fabricated in two different runs. Each die contains twenty single disks and twenty 3-disk arrays at the relative locations indicated in Fig. 4, which also presents SEM photos of each device type.

Devices were tested via an Agilent E5071B Network Analyzer while under 1.5 μTorr vacuum provided by the SUSS PMC150 temperature-controllable vacuum probe station pictured in Fig. 5. The lift and pan capability of probes on the SUSS tool greatly facilitated testing of the many devices required to attain adequate statistical convergence.

A. Single Device Measurements

Fig. 6 compares the measured frequency response characteristics of a stand-alone 61-MHz wine-glass disk and a 3-disk

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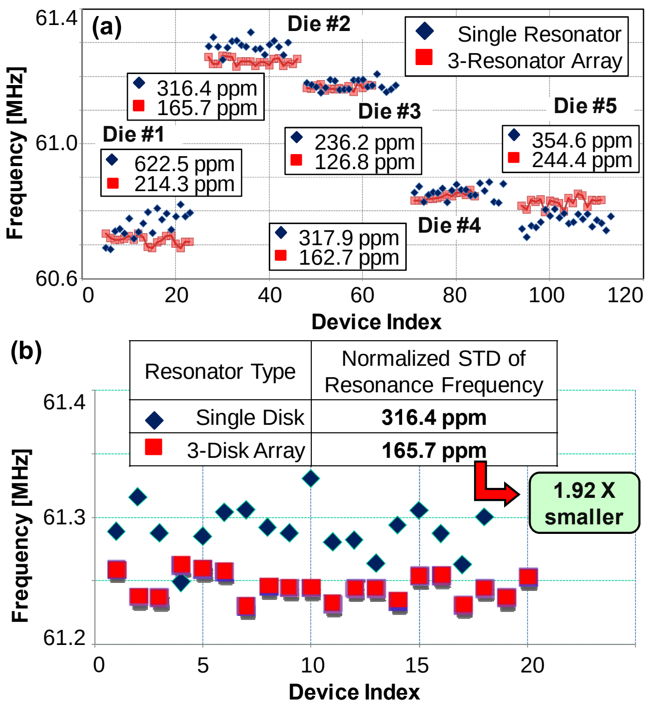

Fig. 7: (a) Raw statistical resonance frequency data gathered from all 5 measured dies. (b) Zoom-in on to the data of die # 2.

array composite of them. As expected, the 3-disk array composite provides a higher peak, which corresponds to a smaller motional resistance. In addition, the Q of the array composite is still quite high, in excess of 120,000, and not much smaller than the 141,000 of a stand-alone wine-glass disk.

B. Measured Statistics

Fig. 7(a) presents a plot of measured frequency versus device index for the 200 disks and array composites from the 5 tested dies. Clearly, the arrays of each die exhibit smaller frequency variations compared to the stand-alone disk devices on the same die. Fig. 7(b) zooms in on the data for die #2, for which the resonance frequency standard deviation of the twenty 3-disk arrays is only 165.7 ppm, which is around 1.92× smaller than the 316.4 ppm exhibited by the twenty stand-alone disk resonators located on the same die. Although a larger number of data points would instill more confidence in this result, the measured ratio of resonance frequency standard deviation between stand-alone disks and 3-disk arrays is very consistent with the theoretical prediction of (6). This seems to support the assumption made in (6)'s derivation that the variations causing frequency shifts in the resonators making up the arrays were largely random, i.e., were uncorrelated.

C. Statistical Benefits of Arraying

Pursuant to gauging the benefits offered by the improved frequency repeatability afforded via arraying, a three-resonator 0.5% bandwidth micromechanical disk filter centered at 150-MHz with a designed ripple of 0.5dB (such as depicted in Fig. 8) was first designed using the methods of [9] assuming perfectly matched constituent resonators, yielding the red simulated curve in Fig. 8. Then, using data from Fig. 7(b), radius variations of σ_{single} = 316 ppm and σ_{array} = 165 ppm were introduced according to the ΔR deviations depicted in Fig. 8,

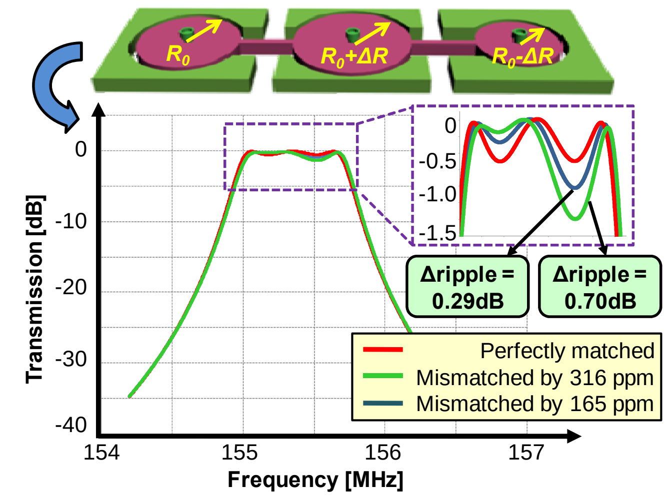

Fig. 8: Simulated transmission curves for a properly designed and terminated 0.5% bandwidth three-pole micromechanical disk filter with no mismatch between resonators (red); $\Delta R/R$ = 165 ppm, for which a passband distortion degradation of 0.29dB is seen; and $\Delta R/R$ = 316 ppm, for which a passband distortion degradation of 0.7dB is seen.

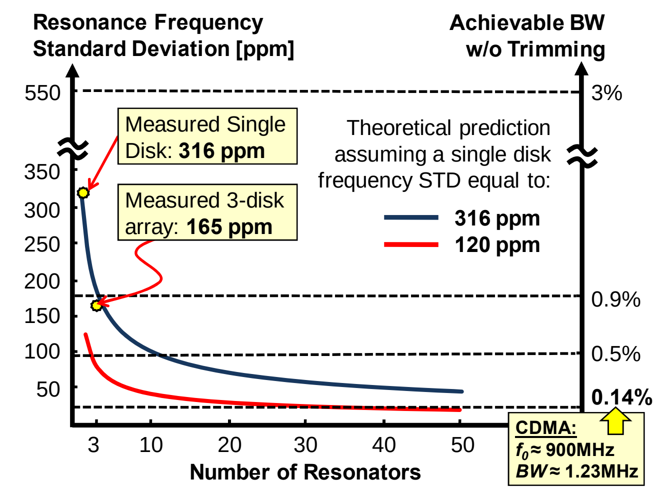

Fig. 9: Theoretically predicted plots of resonance frequency standard deviation for array-composite resonators and the corresponding 90% confidence interval 3-pole filter bandwidth achievable via such resonators without trimming, both versus the number of resonators coupled in the array.

which represent the worst case radial spread among resonators, i.e., the spread of ΔR's yielding the most passband distortion. The results of simulations using these spreads are plotted alongside the ideal simulation in Fig. 8. The filter with 316 ppm radial variation exhibits passband distortion degradation as large as 0.7dB, which is large enough to impact a system application using this filter. The same filter with 165 ppm radial variation shows a much smaller passband distortion degradation, on the order of only 0.29dB, which is often acceptable. Since 165 ppm corresponds to one standard deviation for a 3-disk array composite resonator, a 0.5% bandwidth filter of the type in Fig. 8 but using 3-disk array composites as resonators could be made using our university fabrication process with a 68.2% confidence interval that passband distortions will be less than 0.3dB.

As the number of the resonators coupled in the array increases, (6) dictates that the frequency variation can be further reduced, allowing even smaller percent bandwidth filters without the need for trimming. Fig. 9 illustrates this by plotting the standard deviations achievable by array composites of resonators for single-resonator starting standard deviations of 316 ppm (i.e., the value measured in this work) and 120 ppm, which might be achievable in a more professional foundry than the university one used for this work. The vertical axis on the left indicates the standard deviation for an array composite using the number of resonators indicated in the *x*-axis, while the right vertical axis indicates the corresponding percent bandwidth 3-resonator filter achievable without trimming with a 90% confidence interval. As shown, a prohibitively large number of resonators would be required to bring the standard deviation down to the 20 ppm level required for CDMA channel-selection at 900 MHz using a university fabrication process. However, if a more capable foundry with a 120 ppm single-resonator standard deviation were used, then a composite array of only 27 disks would be required to achieve the 0.14% bandwidth needed for CDMA channel-selection with 90% confidence interval without the need for trimming.

Of course, the above analysis pertains mainly to the case where only variations in the resonators are predominant. In general, variations in the beams coupling the resonators in a filter will also contribute to passband ripple, but the effect of such variations will be less pronounced when the coupling beams are designed with quarter-wavelength dimensions, as described in [9]. The degree to which coupling beam mismatch affects passband distortion is presently under study.

V. Conclusions

The demonstration via this work of standard deviation reductions from the 316 ppm of stand-alone resonators to the 165 ppm of 3-resonator array composites represents a reduction in the expected manufacturable 90% confidence interval trim-free filter percent bandwidth from 1.89% to now just 0.86%. While 0.86% still is not small enough for direct RF channel-selection, it does bring us significantly closer to this, and an RF front-end with 0.86% bandwidth selectivity would still greatly reduce the dynamic range requirements of subsequent receiver electronics over the current 3% bandwidth preselect filters presently in use. The demonstrated reduction of frequency standard deviation via mechanically coupled arraying suggests that if trimming is to be avoided, filters using array composite resonators, such as that of [1] or [15], might be preferred over filter realizations that utilize only stand-alone resonators in their construction. Indeed, it seems that arraying might outright be needed to actually achieve RF channel-select bandwidths of less than 0.14% without trimming.

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