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# Small Percent Bandwidth Design of a 423-MHz Notch-Coupled Micromechanical Mixler

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***Abstract*—Notching and low-velocity coupling design strategies are described and demonstrated that yield the first UHF vibrating micromechanical hollow-disk ring mixer-filters with IF bandwidths down to 0.05%, while still retaining reasonable passband shapes. Specifically, a 423-MHz mixer-filter, comprised of two mechanically coupled resonators exhibiting *Q*'s in excess of 10,000, has been successfully demonstrated with a flat passband bandwidth of only 202 kHz. Like a previous 34-MHz mixer-filter based on clamped-clamped beam resonators, the much higher frequency device of this work is capable of performing both mixing (via capacitive transducer nonlinearity) from an RF frequency down to its IF passband centered at 423 MHz, then very small percent bandwidth filtering, e.g., to remove unwanted interferers in the receive path of a communication handset. The percent bandwidths demonstrated here are small enough to make possible channel-selection much earlier in a receive path chain, which could then greatly enhance the robustness and battery lifetime of future wireless transceivers.**

***Keywords*—micromechanical, electromechanical mixing, mixer-filter, notch, low velocity coupling, percent bandwidth, quality factor**

## I. Introduction

With demonstrated on-chip *Q*'s greater than 10,000 at GHz frequencies, vibrating RF MEMS devices are attracting attention as frequency processing and generation devices that offer an opportunity for a paradigm-shift in future wireless transceiver design [1]. Among the array of vibrating RF MEMS devices published over recent years, micromechanical mixer-filters, or "mixlers" as termed in [2], perhaps achieve the greatest functional density, as they combine both mixing and filtering in a single passive micromechanical device. As an example of the benefits afforded by such a device, Fig. 1 compares the system-block topologies of a conventional super-heterodyne receiver with that of a possible next generation that takes advantage of the tiny size, integrability, and functionality of mixlers. As shown, the mixer-filter combination of the super-heterodyne is replaced by not only one, but by numerous mixlers that are switchable (via the resonator structure lead [2]) in and out of the receive path. In this configuration, the bank of mixlers can perform channel-selection themselves with a fixed local oscillator (LO), that need not be tuned, so that can be designed with excellent phase noise while consuming very little power. In addition, because the micromechanical devices in Fig. 1(b) have much higher *Q*'s than macroscopic resonators at the same frequency, the RF LNA normally needed to recover losses from filters made using lower *Q* resonators is no longer needed. This not only saves more power, but also, raises the dynamic range of the receiver substantially, making it much more robust.

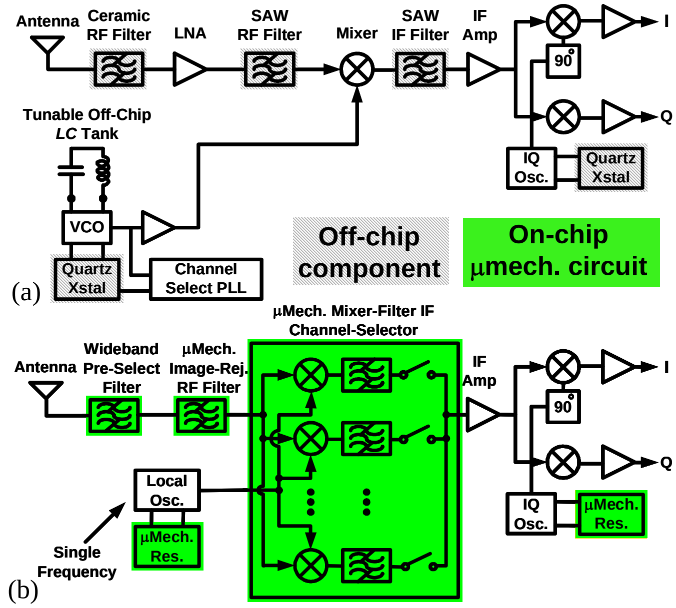


Fig. 1: Expected progression of transceiver front-end architectures when micromechanical mixlers are employed. (a) Present-day super-heterodyne. (b) Low-power MEMS-based receiver architecture using an IF channel-selecting mixler bank.

To date, the highest IF frequency published for any mixler device has only been the 37 MHz of [2]. In both systems of Fig. 1, an IF frequency this low raises the complexity of the image-reject filter, which must use more resonators to effect a steeper passband-to-stopband roll-off. A higher IF frequency (or set of them, for the case of Fig. 1(b)) would allow a much simpler image-reject filter design, while also lowering the frequency of the LO, in turn lowering its power and phase noise. Pursuant to delivering a higher frequency mixler, this paper presents a 423-MHz mixler based upon the UHF "hollow disk" ring resonator of [3] and using notched attachment points for its extensional mode coupling to achieve the small percent bandwidths down to 0.05% needed for channel selection, while still retaining reasonable passband shapes. With *Q*'s >10,000, the resonators in the filter portion of the mixler are well-suited to achieving low insertion loss even for percent bandwidths as small as 0.05%.

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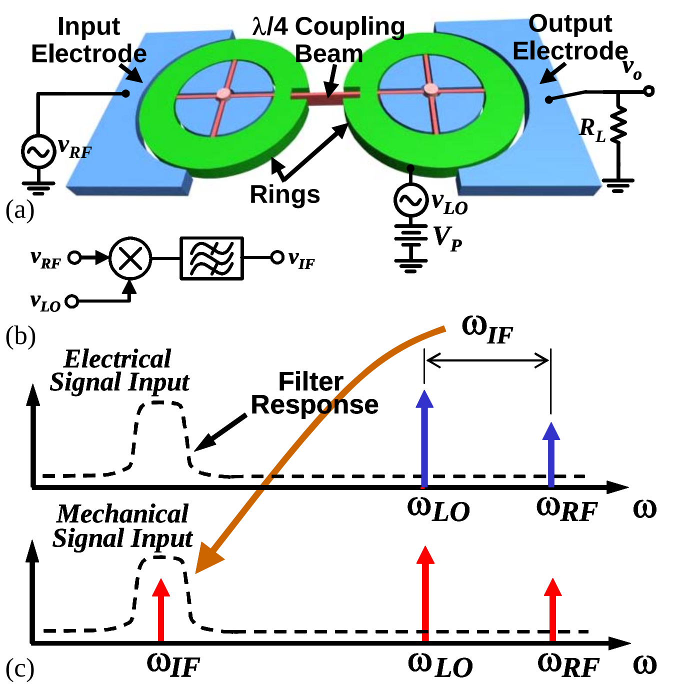


Fig. 2: (a) Perspective-view schematic of a micromechanical hollow-disk ring mixler. (b) Equivalent functional block diagram for the mixler. (c) Electrical and mechanical signal plots illustrating conversion of off-resonance electrical signals at $\omega_{LO}$ and $\omega_{RF}$ down to a force at $\omega_{IF}$, which happens to be in the filter passband in this case.

## II. MIXLER STRUCTURE AND OPERATION

As depicted in Fig. 2(c) and described more fully in [2], a capacitively transduced mixler uses the square-law voltage-to-force transfer function of its transducer to mix two signals (e.g., an LO and an RF signal) down to a force at the IF frequency according to

$$F_i = \frac{1}{2}(V_P + v_{LO} - v_{RF})^2 \left(\frac{\partial C}{\partial r}\right) = \cdots - \frac{1}{2} V_{LO} V_{RF} \left(\frac{\partial C}{\partial r}\right) \cos(\omega_{RF} - \omega_{LO})t + \cdots \quad (1)$$

where $v_{RF} = V_{RF}\cos\omega_{RF}t$ is an RF input signal, $v_{LO} = V_{LO}\cos\omega_{LO}t$ is a local oscillator signal (in this case applied together with the dc-bias $V_P$), and where the mixed force component of interest $F_i$ at ($\omega_{RF}$-$\omega_{LO}$) has been singled out in the last expression. Once the signals are converted or mixed to a force, this force signal is then processed by a micromechanical filter structure, comprised of several resonators coupled by bandwidth-defining mechanical springs [4], that defines the IF frequency and frequency shaping characteristics. Basically, force components out of the filter passband, such as those at $\omega_{RF}$ and $\omega_{LO}$, are rejected; while those in the passband, such as if $\omega_{RF}$-$\omega_{LO}$=$\omega_{IF}$, are passed.

In order to achieve UHF frequency, the two-resonator filter structure of the mixler in Fig. 2(a) replaces the clamped-clamped beam resonators previously used in [2] with the "hollow-disk" ring resonators of [3], and replaces the flexural-mode beam mechanical coupler of [2] with a quarter-wavelength longitudinal-mode coupling beam attached at

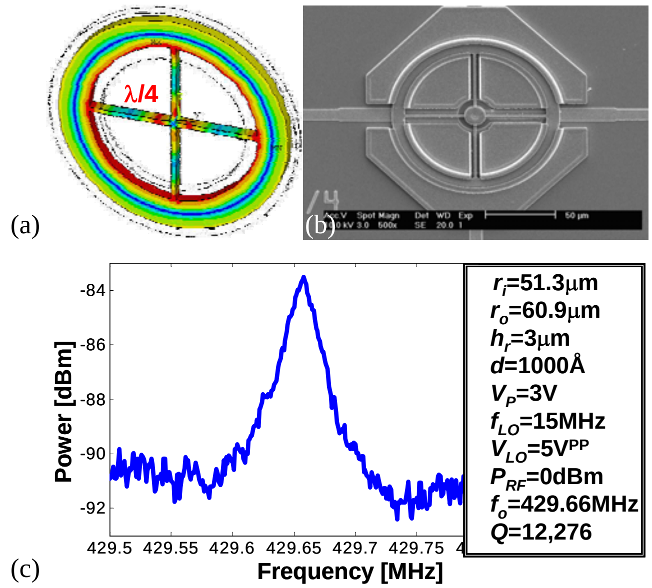


Fig. 3: (a) ANSYS simulated mode shape, (b) global-view SEM, and (c) measured spectrum for a fabricated 430-MHz micromechanical hollow-disk ring resonator with quarter-wavelength "spoke" supports.

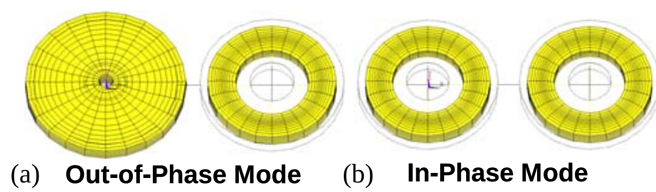


Fig. 4: Finite element simulated mode shapes for a λ/4-coupled micromechanical hollow-disk ring filter. (a) Out-of-phase mode. (b) In-phase mode. (Fig. 6 shows mode peaks in the filter spectrum.)

notched locations. The particular structure of this work did not use a non-conductive coupling beam, so the dc-bias $V_P$ and LO signal are both applied to the whole structure (rather than to separate electrodes [2]) in order to effect the desired mixer-filter function depicted in Fig. 2(c). Like the devices of [3], the constituent ring resonators use non-intrusive quarter-wavelength "spoke" supports to allow $Q$'s greater than 10,000 when operating in an extensional mode (c.f., Fig. 3(a)) at 430 MHz, as evidenced by the frequency characteristic in Fig. 3(c) measured for the device of Fig. 3(b). With resonator $Q$'s this high, filters using such "hollow-disk" ring resonators should be able to achieve filter percent bandwidths less than 0.05% at IF with little insertion loss penalty.

As with any mechanical filter, the coupled two-resonator structure in Fig. 2(a) exhibits two-mechanical resonance modes with closely spaced frequencies that define a passband. The center frequency of the passband is determined primarily by the frequencies of the constituent resonators, while the spacing between modes (i.e., the bandwidth) is determined largely by the stiffness of the coupling spring and resonator stiffness. As shown in Fig. 4, each mode peak corresponds to a distinct, physical mode shape: If the coupling beam dimensions correspond to $m\lambda/4$ at the center frequency, where $m$ = 1, 5, 9, …, then in the lower frequency mode, the resonators are 180˚ out of phase (i.e., the coupling beam acts as a rigid body); and in the higher frequency mode, both resonators vibrate in

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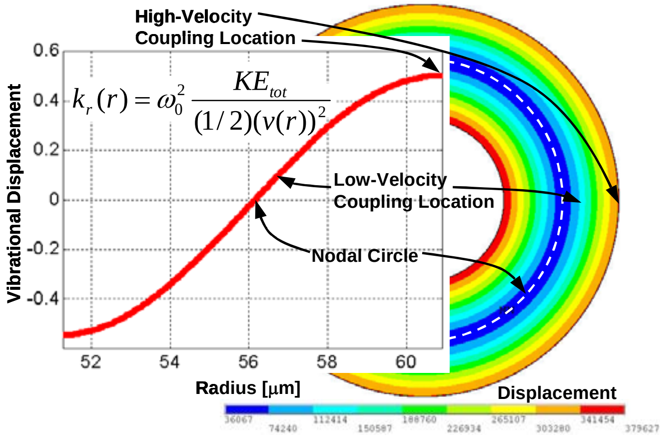


Fig. 5: Finite element simulated mode shape for a micromechanical ring resonator with an expression for stiffness at any location on the ring and arrows relating points on a vibrational displacement (equivalent to velocity) curve with locations on the ring. In the expression, $KE_{tot}$ is the total kinetic energy in the vibrating system, and $v(r)$ is the velocity at location $r$.

phase (i.e., the coupling beam vibrates longitudinally). If the coupling beam dimensions correspond to $n\lambda/4$ at the center frequency, where $n$ = 3, 7, 11, …, then the relative low and high frequency phasings are reversed from the above.

## III. Notched Low Velocity Coupling

The overall percent bandwidth ($P_{BW} = BW/f_0$) attainable via a mechanical filter structure is proportional to the ratio of coupling spring stiffness $k_s$ to the resonator stiffness $k_r$ at the attachment location, and is given by

$$P_{BW} \propto \frac{k_s}{k_r} \qquad (2)$$

For the case of macroscopic mechanical filters, $k_s/k_r$ can be made quite small, because the resonators are often much bigger and thicker than their associated coupling springs [5]. In contrast, the resonators and couplers in micromechanical filters are usually of similar size, and thus, the ratio $k_s/k_r$ is limited. This, then, limits the attainable filter percent bandwidth. Without a clever method for amplifying $k_r$, sub-micron coupling beam dimensions might be needed to achieve small percent bandwidth, making fabrication more difficult (i.e., lowering fabrication yields).

To circumvent the above limitation, $k_r$ was amplified in [4] via method called low velocity coupling, which recognized the fact that the dynamic stiffness $k_r$ of a resonant device is much higher at locations where the velocity of motion is small, so attached the coupling beam to low velocity locations of the coupled resonators. In [4], low velocity attachment locations could be accessed by merely choosing locations closer to the anchors of clamped-clamped beams. For the present ring resonator, low velocity locations can be found at nodal points on the ring, which are illustrated on the finite element-simulated displacement topography of Fig. 5. Fig. 5 also includes the expression for the dynamic stiffness at any location on the ring, which is seen to be inversely proportional to the square of velocity (or displacement, since displacement and velocity are directly proportional at resonance). From this equation, the resonator stiffness obviously becomes smaller at

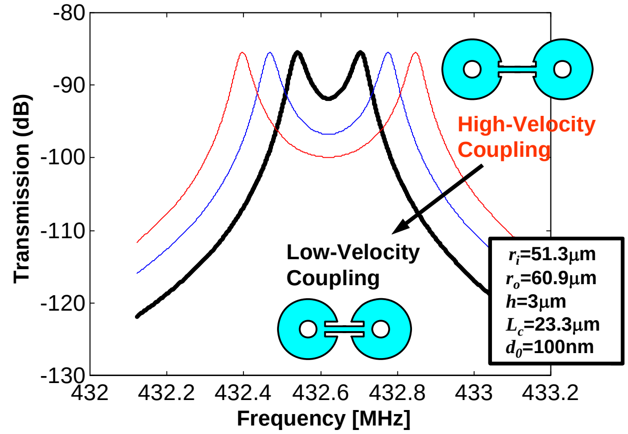


Fig. 6: Simulated frequency response spectra for a micromechanical hollow-disk ring mixler with varying coupling attachment notch depths.

the locations close to the nodal low-velocity circle. Thus, by coupling the hollow-disk rings close to their nodal points, rather than at the outer perimeter of the ring, smaller $k_s/k_r$ can be attained, and thus smaller $P_{BW}$ can be achieved, even when the resonators and coupling springs have similar sizes.

To access low velocity coupling locations, this work simply cuts notches into the ring structure, where the velocity of the coupling location depends upon the depth of the notch. This very simple method, which does not appreciably affect ring resonator performance, allows the use of a set coupling beam geometry for all filters on a given die. In other words, the coupling beam need not be redesigned to accommodate filters with different bandwidths; only one quarter-wavelength coupling beam need to be designed with a specific length, width, and thickness, and the filter bandwidth varied by simply choosing the right notch depth at attachment locations. Thus, not only are all filter characteristics governed by lateral dimension, and thus by CAD layout amenable to automated computer generation; but fabrication yield is enhanced due to the use of identical coupling beam dimensions.

Fig. 6 presents simulated frequency characteristics for a ring mixler with varying coupling locations, i.e., varying notch depths at attachment points. Clearly, the closer the attachment to the nodal circle, the smaller the filter percent bandwidth.

## IV. Fabrication and Experimental Results

2-µm-thick hollow-disk ring mixlers with 100 nm electro-to-resonator gaps were fabricated via a three-polysilicon self-aligned-and-filled stem process used previously to achieve GHz frequency ring resonators [3]. Fig. 7 presents SEM's of a fabricated hollow-disk ring mixler, with zoom-ins on its gap spacing and coupling attachment points, clearly showing the use of notching to achieve low-velocity coupling, and thereby small percent bandwidths.

To test mixlers, the setup shown of Fig. 2(a) was used, with an RF input signal supplied by a network analyzer, the LO by a signal generator, and with the output motional current measured in the IF range (i.e., the filter bandpass range) by a spectrum analyzer in MAX HOLD mode, where the spectrum analyzer retains the highest measured value captured at the frequency of the signal being measured. In MAX HOLD mode,

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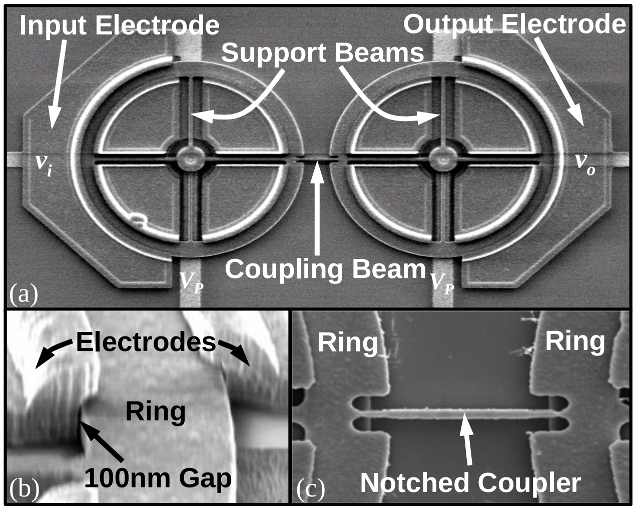


Fig. 7: (a) Wide-view, (b) gap-zoomed, and (c) notch-coupler-zoomed SEM’s of a fabricated 423-MHz micromechanical hollow-disk ring mixler.

the spectrum analyzer essentially behaves like a network analyzer, but collects data at an output frequency (i.e., IF) different than the input (i.e., RF) frequency delivered to the device under test. Several sweeps are generally needed to average the measured signal and obtain sufficiently smooth spectra.

Fig. 8 presents the unterminated frequency characteristic measured using this setup for a 2μm-thick hollow-disk ring mixler in vacuum with a 1.8μm coupling attachment notch depth, showing a center frequency of 431.4 MHz with percent bandwidth of 0.088%. Fig. 9 presents the unterminated frequency characteristic for a similar device, but this time with a 3.8μm notch depth, now with a center frequency of 426.33 MHz with a smaller percent bandwidth of 0.07%. Fig. 10 finally presents a percent bandwidth of only 0.047% at 422.63 MHz, obtained using a coupling attachment right at the nodal circle of the ring structure (or at least as close as we could get). Clearly, notching controls filter bandwidths, and the deeper the notch, the smaller the percent bandwidth.

## V. CONCLUSIONS

Using coupling beams attached at notched low-velocity locations, a 423-MHz hollow-disk ring mixler has been demonstrated with measured IF percent bandwidths as low as 0.047%, while retaining a relatively flat passband. The mixler IF bandwidths are quite programmable via specification of attachment notch depths, and quite amenable to CAD layout and automatic computer generation. Although not demonstrated with proper terminations in this work, the *Q*’s >10,000, the resonators in the filter portion of the mixer-filter are well-suited to achieving low insertion loss, even for percent bandwidths as small as 0.05%. Such a small percent bandwidth would make possible channel-selection much earlier in a receive path chain, which could then greatly enhance the robustness and battery lifetime of future wireless transceivers.

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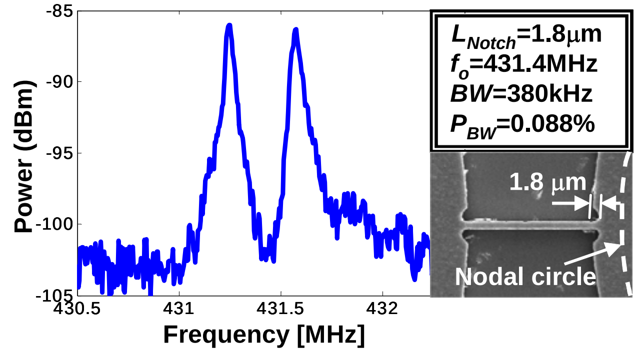


Fig. 8: Measured frequency characteristic for a 1.8μm notch-coupled micromechanical hollow-disk ring mixler.

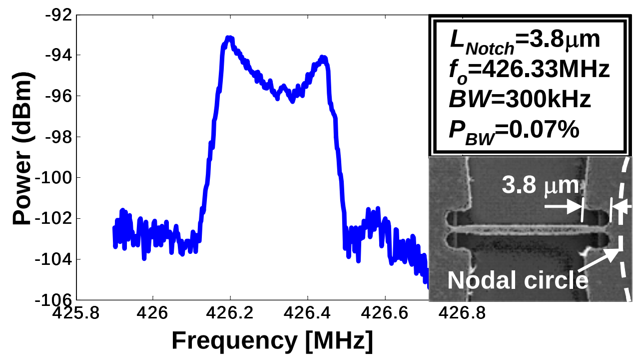


Fig. 9: Measured frequency characteristic for a 3.8μm notch-coupled micromechanical hollow-disk ring mixler.

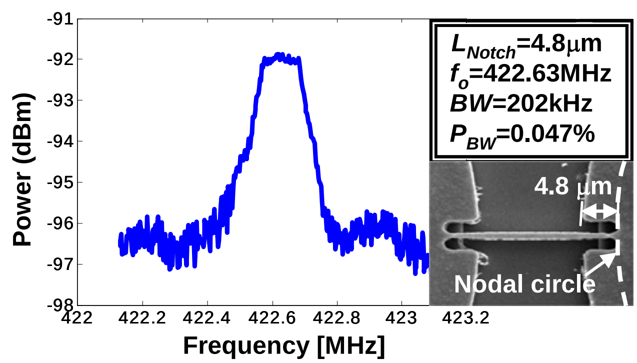


Fig. 10: Measured frequency characteristic for a 4.8μm notch-coupled micromechanical hollow-disk ring mixler.

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