ABSTRACT

This paper reports experimental results on a new class of single-chip multiple-frequency (up to 236 MHz) filters that are based on low motional resistance contour-mode aluminum nitride piezoelectric micromechanical resonators. For the first time, aluminum nitride rectangular plates and rings have been electrically cascaded to yield high performance, low insertion loss (as low as 4 dB at 93 MHz) micromechanical band pass filters. This novel technology could revolutionize wireless communication systems by allowing the co-fabrication of multiple frequency filters (IF and RF) on the same chip, therefore reducing form factors and manufacturing costs. In addition, these filters require terminations on the order of kΩ, thereby making possible their direct interface with standard 50 Ω systems.

Keywords: Piezoelectric resonators, contour-mode resonators, micromechanical filters.

INTRODUCTION

As the demand for ubiquitous connectivity grows, the expectations of wireless appliances’ functionality and interchangeability are getting more and more exacting. RF MEMS is an emerging technology that promises to enable both new paradigms in RF systems as well as unreported levels of performance and integration. Main drivers of research in RF MEMS technology are resonator-based circuits, namely filters and oscillators. Solutions capable of integrating multi-band and multi-standard devices that consume low power and have small form factors will accomplish the vision of next-generation, ubiquitous wireless communications.

Several research groups [1-3] have demonstrated individual or coupled electrostatically-driven microresonators. Although characterized by sheer high Q, these microdevices suffer from large motional resistance, Rm. For filters, a large Rm translates into the need for extremely bulky coupling elements and makes these resonators unintegrable with existing 50 Ω systems. Piezoelectric materials such as aluminum nitride or quartz offer larger electromechanical coupling coefficients that reduce the motional resistance of the resonators to few ohms. Piezoelectric resonators such as FBARs [4-5] and shear-mode quartz resonators [6], have been successfully demonstrated and electrically cascaded to form band pass filters in the GHz range. Because film thickness sets the center frequency of these resonators, FBARs and shear-mode quartz resonators do not permit the manufacturing of a single-chip RF module, having multiple-frequency selective filters on the same substrate.

For the first time, this work realizes multiple-frequency, band pass filters on the same chip, showing a revolutionary pathway for single-chip, multiband, integrated solutions. Using a novel and disruptive MEMS resonator technology based on the excitation of contour mode shapes in AlN microstructures [7-8], our research group was able to demonstrate band pass filters at 93 and 236 MHz, by electrically cascading up to eight resonators in a ladder structure. These filters show very promising performance, being characterized by low insertion losses (4 dB at 93 MHz), large close-in and out-of-band rejection (~ 40 dB and ~ 27 dB, respectively, for a 93 MHz filter) and fairly sharp roll-off with a 20 dB shape factor of ~ 2.2. The filters described in this paper are about 30X smaller than existing SAW technology, commonly used in the IF bands for cell phones. In addition, with a temperature coefficient of ~ -25 ppm/°C, they have 40% lower temperature sensitivity than SAW filters.

FILTER DESIGN

Contour-mode rectangular plate [7] and ring-shaped [8] AlN resonators are the building blocks for the band pass filters of this work. Figure 1 shows a schematic representation of ring-shaped and rectangular plate resonators (with their mode shapes) that are used as building elements of filter arrays. The basic ladder filter configuration is composed of series and shunt resonators (Fig. 2a) to form an L network. Then these networks can be cascaded to form more complicated multi-pole filters.

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**Fig. 1:** Schematic views of the building blocks for the filters and their mode shapes: (a) circular ring AlN resonator excited in a radial-extensional contour mode shape; (b) rectangular plate AlN resonator excited in a width-extensional contour mode shape.
These networks have been analyzed using an ABCD matrix approach [9]. For an initial proof of concept, high order filters (3rd and 4th) were built by simply cascading L networks.

When designing band pass filters we would like to optimize a few parameters, so that symmetrical group delay, low insertion losses and large out-of-band rejection can be achieved. In order to provide a symmetrical group delay the filter termination, $R_{\text{term}}$, should be chosen to be the geometric mean of the series and shunt resonator reactances [9]:

$$R_{\text{term}} = \frac{1}{\omega_c} \sqrt{\frac{1}{C_p C_s}}$$

(1)

where $\omega_c$ is the filter center frequency, and $C_p$ and $C_s$ are the parallel capacitance of the shunt and series resonators, respectively. Maximum $S_{21}$ is obtained when the parallel resonance of the shunt branch, $f_{PP}$, coincides with the series resonance of the series branch, $f_{SS}$. In this condition, the insertion losses can be expressed as:

$$I.L. \approx 1 - \frac{n}{\omega_c C_s R_{\text{term}} k^2 Q}$$

(2)

where $n$ is the number of L networks, $k^2$ is the effective electromechanical coupling of AlN [9] and $Q$ is the quality factor of the individual series resonators. It is clear that large $k^2$ and $Q$ are therefore desired in order to minimize losses. Out-of-band rejection is set by the capacitance ratio between the series and shunt branch and by the number of L stages:

$$S_{21, \text{Out-of-Band}} \approx \frac{1}{\left(1 + \frac{C_s}{2C_s}\right)^n}$$

(3)

The fractional bandwidth of the filter is set by the distance between the two zeros (the parallel resonance of the series branch, $f_{SS}$, and the series resonance of the shunt branch, $f_{SP}$, respectively) of the filter transfer function. Ultimately this translates into:

$$\frac{f_{SP} - f_{SS}}{f_c} \approx \frac{8}{\pi^2} k^2$$

(4)

Therefore, the bandwidth of the filter depends on the electromechanical coupling coefficient and is theoretically limited to a maximum of $\sim 2.5\%$, unless other external elements are used.

It is clear that the principal parameters on which the designer can act are the values of the parallel capacitance of the series and shunt resonators as well as their ratio and the number of stages required. In order to minimize insertion losses and at the same time guarantee very good out-of-band rejection, a maximum number of 3 or 4 stages should be selected. The capacitance ratio should be chosen so that good out-of-band rejection can be obtained while maintaining high-Q resonators (in [8] it was reported that Q degrades when the inner radius of the ring is shrunk) and small terminations. In this work capacitance ratios of 1 and 0.67 were used.

**FABRICATION PROCESS**

A simple four-mask, low-temperature, potentially post-CMOS compatible ($T_{\text{max}} < 400$ °C) process (Fig. 3) has been used to fabricate these devices. The process flow is substantially the same reported in [8], and uses conventional micromachining technique to manufacture high quality AlN resonators with high yield. A single resonator consists of a 2µm AlN film sandwiched between a bottom platinum electrode (~ 100 nm thick) and a top aluminum electrode (~ 175 nm thick). AlN films are sputter-deposited using an AMS PVD tool and exhibit rocking curve values as low as 1.3° on Pt seed.
The only difference with respect to the fabrication process described in [8] involves performing the wet etch of AlN to access the bottom electrode before the deposition and patterning of the top Al electrode. This step is required to implement a ladder filter topology, for which contact between the top and bottom electrodes is required.

As it was shown in Fig. 2b, the parallel resonance of the shunt branch should coincide with the series resonance of the series branch for the filter to work properly. The shift can be defined directly during the processing step used for patterning the Pt electrode. The Pt electrode has a very large mass density, about 6.5X the one of AlN. By removing small amounts of Pt it is possible to raise the center frequency of the resonator. Being most of the strain (and consequently charge) concentrated in the middle of the structure, we can lithographically remove small amounts of Pt from the edges of the microstructures (Fig. 4) without affecting the overall performance of the resonators. The loading mechanism can be explained by a simple analytical model based on vibration techniques [10] and was experimentally verified. This study yielded that for a 100 nm thick Pt the center frequency of a 90 µm inner radius ring structure shifts by ~ 7000 ppm for each µm of Pt that is removed from the width of the structure, and the center frequency of a 200 µm by 50 µm rectangular plate shifts by 500 ppm for each µm of Pt that is removed from the length of the structure.

Another way to achieve the frequency shift is by changing the dimensions of the inner radius of the rings. By having a ring in the shunt branch with a diameter larger than the one in the series branch, we can lower the resonance frequency of the resonators in the shunt branch, while increasing the out-of-band rejection. Although this technique is very promising, it has intrinsic drawbacks in terms of larger form factors and additional parasitic capacitance and resistance (longer traces are needed in order to route the signal).

### EXPERIMENTAL RESULTS

The fabricated micromechanical filters were tested in a RF probe station at atmospheric pressure. Ground-Signal-Ground (GSG) probes were used. Two-port S-parameter calibration (SOLT) was performed using short, open and through reference structures directly fabricated on the die under test, whereas a 50 Ω resistor on a ceramic substrate was used as a load reference. Full S-parameter matrices were extracted for each filter using an Agilent E5071B network analyzer. No external terminations were

![Fig. 5](image-url): (a) Electrical response of a band pass filter constituted by eight ring-shaped resonators arranged in a ladder configuration. The resonators had individual Q in the order of 1,000. (b) Large scan of the same filter response from 0 to 1 GHz. 50 Ω terminations were used in this scan.
connected to the device under test. The network analyzer permits to automatically change the terminations and compute the filter transmission spectrum.

Eight rings, all with an inner radius of 90 µm and 20 µm width, were electrically cascaded in a ladder structure. The frequency of the series and shunt branches were shifted by ~0.3%. It is important to note that a wider bandwidth could be obtained, but extra parasitic capacitance intrinsic to the fabrication process limited the overall bandwidth. This filter shows fairly moderate insertion losses of ~7.9 dB at 236.2 MHz, an out-of-band rejection of 26 dB and a 20dB shape factor of 2.79 (Fig. 5). It is interesting to note that this filter does not suffer from any other spurious resonance (Fig. 5b). The non-ideal shape factor is probably due to slight mismatches in frequency between adjacent resonators. As discussed in section 3, the frequency shift was also defined by changing the size of the inner radius of the rings in the shunt branch (inner radius of 140 µm was used in the shunt branch and 90 µm in the series branch). Up to six rings were connected in this configuration. Although the results are promising, large insertion losses (~11.3 dB) at 236 MHz were recorded, and probably inherently due to the longer traces needed to connect the resonators. Four, six and eight 200 µm long and 50 µm wide rectangular plates were tested in a ladder configuration. The frequency of the series and shunt branches were changed by ~0.3%. It is important to note that a wider bandwidth could be obtained, but extra parasitic capacitance intrinsic to the fabrication process limited the overall bandwidth. This filter shows fairly moderate insertion losses of ~7.9 dB at 236.2 MHz, an out-of-band rejection of 26 dB and a 20dB shape factor of 2.79 (Fig. 5). It is interesting to note that this filter does not suffer from any other spurious resonance (Fig. 5b). The non-ideal shape factor is probably due to slight mismatches in frequency between adjacent resonators. As discussed in section 3, the frequency shift was also defined by changing the size of the inner radius of the rings in the shunt branch (inner radius of 140 µm was used in the shunt branch and 90 µm in the series branch). Up to six rings were connected in this configuration. Although the results are promising, large insertion losses (~11.3 dB) at 236 MHz were recorded, and probably inherently due to the longer traces needed to connect the resonators. Four, six and eight 200 µm long and 50 µm wide rectangular plates were tested in a ladder configuration as well. Again the frequencies were shifted by about 0.3%. An example of the electrical response of eight rectangular resonators is shown in Fig. 6. In this case insertion losses as low as ~4 dB were recorded at 93.2 MHz; out-of-band rejection of 27 dB were achieved. As shown in Fig. 6b a second band pass filter exists due to the length-extensional mode shape present in the plate. This mode cannot be suppressed, but could be pushed further down in frequency by changing the aspect ratio of the microstructures. The results for four and six rectangular resonant filters are summarized in Table I.

Table 1: Response parameters of band pass filters built using rectangular plate resonators.

<table>
<thead>
<tr>
<th>Number of Resonators</th>
<th>( f_c ) [MHz]</th>
<th>( \text{BW}_{3dB} ) [kHz]</th>
<th>I.L. [dB]</th>
<th>20dB S.F.</th>
<th>( R_{term} ) [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>93.5</td>
<td>456</td>
<td>-2</td>
<td>N.A.</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>93.1</td>
<td>332</td>
<td>-4.7</td>
<td>2.7</td>
<td>2</td>
</tr>
</tbody>
</table>

CONCLUSIONS

For the first time contour-mode AlN piezoelectric resonators have been electrically coupled in a ladder structure to form low insertion loss, band pass filters at 93 and 236 MHz. Although the performance of these filters are not yet optimized, they promise to open a revolutionary pathway for single-chip multi-frequency, integrated band pass filter solutions characterized by higher performance and smaller form factors. Ongoing research is focusing on expanding the bandwidth of the filters as well as introducing this technology into the GHz frequencies.

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References