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Channel-Select RF MEMS Filters Based On Self-Coupled A1N Contour-Mode Piezoelectric Resonators

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Abstract

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Keywords

aluminum nitride (A1N), contour-mode resonator, channel-select filter, microelectromechanical systems (MEMS)

Comments

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Abstract — **This paper reports experimental results on a new class of single-chip multi-frequency channel-select filters based on self-coupled aluminum nitride (AlN) contour-mode piezoelectric resonators. For the first time, two-port AlN contour-mode resonators are connected in series and electrically coupled using their intrinsic capacitance to form multi-frequency (94 – 271 MHz), narrow bandwidth (~ 0.3%), low insertion loss (~ 4 dB), high off-band rejection (~ 60 dB) and extremely linear (*IIP3* ~ 110 dBm) channel-select filters. This novel technology enables multi-frequency, high-performance and small form factor filter arrays and makes a single-chip multi-band RF solution possible in the near future.**

Keywords — Aluminum nitride (AlN); contour-mode resonator; channel-select filter; microelectromechanical systems (MEMS)

I. INTRODUCTION

Key issues for the realization of next generation wireless devices are efficient spectral utilization, high level integration and low power consumption. In order to adaptively make use of the electromagnetic spectrum, a transceiver will need to selectively process radio frequency (RF) signals over a wide frequency range and rapidly switch from one band to another. An essential part of this multi-band analog signal processor is an array of multi-frequency narrow-band channel-select filters that can be integrated with other components, like switches and oscillators, to form a single-chip multi-band RF solution.

A recently emerged and very promising solution to synthesize integrated, high-performance and narrow-band filters is based on high quality factor, *Q*, MEMS resonators. Several research groups have been developing MEMS resonator technologies based on electrostatic [1, 2] and piezoelectric [3] transduction mechanisms that are capable of providing multiple frequencies of operation on the same silicon substrate (in contrast with conventional FBAR or quartz crystal technologies for which only one frequency per substrate is possible). Among these, aluminum nitride (AlN) contour-mode MEMS resonators [4] stand out as the most promising technology capable of immediately satisfying the critical requirements of the rapidly developing wireless industry. It is currently the only technology that can reliably span a wide frequency range from 10 MHz up to several GHz (operating in the fundamental mode of vibration) on the same silicon chip, and simultaneously offer high Q in air (1,000 – 4,000) and low motional resistance (25 – 700 Ω), which makes the resonators readily matched to conventional 50 Ω RF systems.

Employing this new AlN contour-mode MEMS technology, VHF band-pass filters have been demonstrated by electrically cascading resonators in a ladder topology [5]. The implementation of ladder filters requires the ability to manufacture resonators with different resonant frequencies for the series and shunt branches. Depending on the bandwidth specification, a ladder filter may require a frequency shift in the resonator ranging between 0.1% and 3%, which poses a tremendous challenge on the ultimate achievable yield. Furthermore, the off-band rejection was measured to be ~ 27 dB causing severe limitations on channel-select applications. In this work we propose a new topology to implement multi-frequency (94 – 271 MHz), narrow bandwidth (~ 0.3%), low insertion loss (~ 4 dB), and high off-band rejection (~ 60 dB) channel-select filters. For the first time, three and four single-frequency two-port AlN contour-mode resonators are connected in series and coupled electrically by their intrinsic capacitance to form high-performance filters. Compared to the classical ladder filter implementation, this new coupling technique reduces the overall chip size by employing fewer components, improves manufacturing yield by using single-frequency resonators and easily increases filter off-band rejection without the need to resort to different size resonators.

II. ANALYSIS

Resonators can be coupled mechanically or electrically to form band-pass filters [5, 6]. Electrical coupling is, in general, simpler to realize and does not pose extreme manufacturing challenges. In this work, we will use the intrinsic capacitance to ground present in two-port AlN contour-mode resonators as the coupling elements to design 3rd and 4th order filters.

A. Two-Port AlN Contour-Mode Resonators

In Fig. 1, the micrograph and corresponding schematic representation of a two-port piezoelectric AlN contour-mode resonator are presented. The resonator consists of a 2 µm AlN film sandwiched between two Platinum (Pt) thin film layers. The bottom Pt layer is a single electrode connected to electrical ground, while the top Pt layer is patterned into four parallel electrodes, two of which (red parts in Fig. 1) are connected together to form the input port (P1). The other two connected electrodes (pink parts in Fig. 1) form the output port (P2) of the two-port resonator. The device is symmetrical both electrically and mechanically, so the roles of the input and output ports can be switched. Since each AlN block with electrodes on two parallel surfaces constitutes a one-port rectangular contour-mode resonator [3], both of the input and output ports can be treated as two one-port sub-resonators electrically connected in parallel. Each of the sub-resonators is of length, L, and width, W, as shown in Fig. 1.

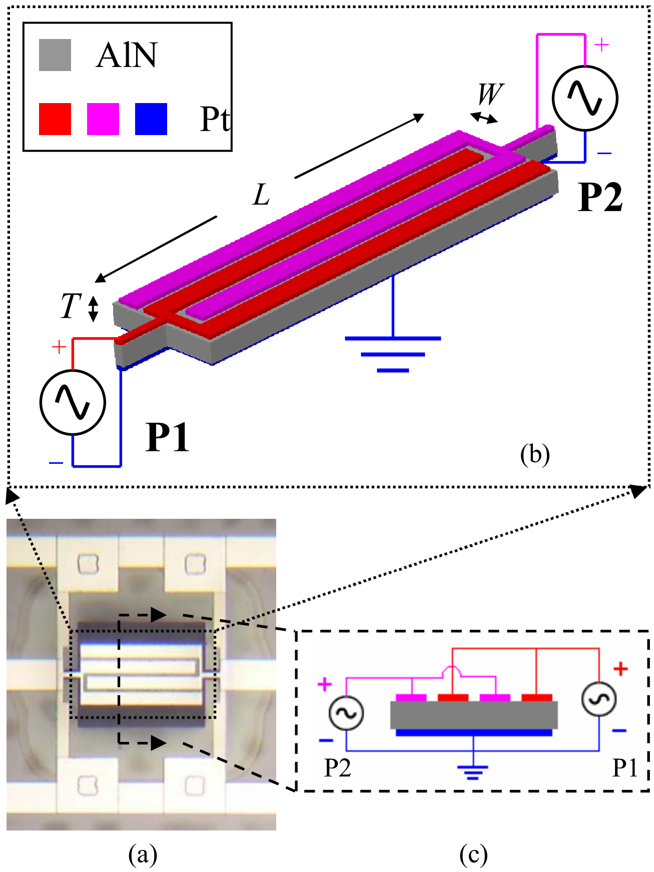

Fig. 1. (a) Micrograph, (b) 3-D schematic and (c) cross-sectional schematic of a two-port AlN contour-mode piezoelectric resonator.

In the following analysis, we will assume P1 to be the input (actuating) port while P2 is the output (sensing) port. When an AC signal is applied to P1 (formed by red and blue electrodes), the vertical electric field across the AlN film induces in-plane dilation or contraction of the resonator body. If the signal frequency coincides with the intrinsic natural frequency of the structure, a contour mode of vibration [4] will be excited and the corresponding mechanical strain (therefore stress) will be induced in the whole rectangular plate. Because of the direct piezoelectric effect, surface charge is generated and collected by the sensing electrodes of P2 (formed by pink and blue electrodes).

B. *Equivalent Circuit Model*

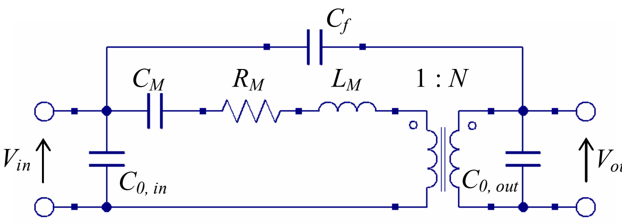

Fig. 2. BVD equivalent circuit model of a two-port piezoelectric resonator.

As derived in [7], the electrical behavior of a piezoelectric resonator can be described by an equivalent circuit according to the Butterworth-Van Dyke (BVD) model. By applying the BVD model to both input and output sub-resonators, the combined equivalent circuit for the two-port resonator is given in Fig. 2. In this case we assumed perfect mechanical energy exchange between the sub-resonators and used R_M to account for all the energy loss in the resonator. Then, the lumped equivalent circuit parameters for the two-port resonator can be expressed as

$$C_{0,in} \approx 2\varepsilon_{33}\varepsilon_0 \frac{WL}{T}, \qquad C_{0,out} \approx 2\varepsilon_{33}\varepsilon_0 \frac{WL}{T}, \qquad N = 1,$$

$$R_M = \frac{\pi}{8}\frac{T}{L}\frac{\rho_{eq}^{1/2}}{E_{eq}^{3/2} d_{31}^2 Q}, \qquad L_M = \frac{\rho_{eq}}{8}\frac{WT}{L}\frac{1}{E_{eq}^2 d_{31}^2},$$

$$C_M = \frac{8}{\pi^2}\frac{LW}{T} E_{eq} d_{31}^2, \qquad \omega_c = 2\pi f_c = \frac{\pi}{W}\sqrt{\frac{E_{eq}}{\rho_{eq}}} \qquad (1)$$

where ε_0 is the permittivity of free space, ε_{33} is the dielectric constant of AlN along the c-axis; L, W and T refers to the length, width and thickness of the sub-resonator respectively; E_{eq} and ρ_{eq} are the equivalent in-plane modulus of elasticity and mass density of AlN and the stacked electrodes; d_{31} is the (3, 1) entry in the AlN's d-form piezoelectric coefficient matrix; ω_c (f_c) is the resonant frequency and Q is the quality factor. The feed-through capacitance C_f is used to account for the parasitic capacitances through the substrate, the AlN film and air.

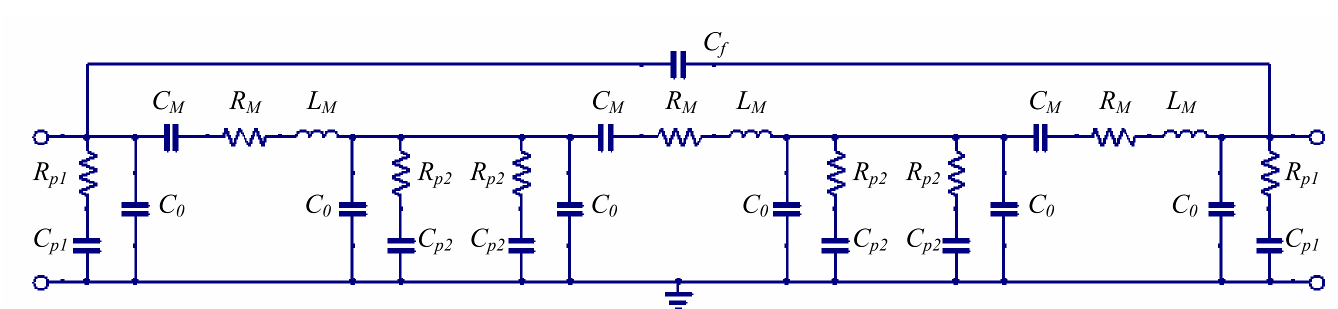

Fig. 3. Overall equivalent circuit model of a 3rd order channel-select filter based on self-coupled AlN contour-mode resonators.

Table I. Measurement results of channel-select filters based on self-coupled AlN contour-mode resonators.

f_c [MHz]	*IL* [dB]	RBW_{3dB}	*Rejection* [dB]	SF_{30dB}	SF_{50dB}	*Order*	R_{term} [Ω]
94	5.4	0.20%	60	4.20	8.70	3	800
271	4.2	0.34%	56	3.76	6.61	3	2000
271	5.1	0.32%	60	2.33	5.25	4	2000

f_c: center frequency; *IL*: insertion loss; *RBW*: relative bandwidth; *SF*: shape factor; R_{term}: termination resistance

In our filter design, several two-port AlN resonators are connected in series and coupled by their intrinsic capacitance ($C_{0,in}$ and $C_{0,out}$) to realize high-order filtering. This solution offers the possibility to realize filters with good shape factors and off-band rejection without the need for different frequency devices. The overall equivalent circuit for such a self-coupled 3rd order filter is obtained by electrically cascading the models of each two-port resonator, as shown in Fig. 3. The parasitic components (R_{p1}, C_{p1}, R_{p2} and C_{p2}) are added to account for substrate loss and capacitance between the signal and ground electrode lines.

To simplify the analysis of the filter response, we will first neglect the effect of parasitic components. For the 3rd order filter in Fig. 3 with the two ports terminated by a matching resistance, R_{term} (approximately equal to $|1/(j\omega_c C_0)|$), the insertion loss can be approximated by

$$IL(\text{dB}) \approx -20\log_{10}\left(\frac{4}{4+3\pi^2/k_t^2 Q}\right) \qquad (2)$$

which is a function of the effective electromechanical coupling coefficient k_t^2 [5] and the quality factor Q of the two-port resonators. The out-of-band rejection is primarily determined by the feed-through capacitance C_f and can be expressed as

$$Rej.(\text{dB}) \approx -20\log_{10}\left(\frac{C_f}{C_0}\right) - IL \qquad (3)$$

which can be controlled by designing the physical distance between the input and output ports. According to the theory given in [6], the relative bandwidth f_{BW}/f_c can be calculated as

$$RBW_{3\text{dB}} \approx \sqrt{\frac{3C_M}{2C_0}+1}-1 \approx \frac{3}{\pi^2}k_t^2 \qquad (4)$$

which is again set by the effective electromechanical coupling coefficient k_t^2 of AlN.

III. Experimental Results

The filters were fabricated using a simple four-mask, low-temperature, potentially post-CMOS compatible process. The two Pt layers were sputter-deposited and patterned by lift-off. The AlN layer in between was sputter-deposited using a Tegal/AMS® PVD tool and exhibits rocking curves as low as 1.2˚. The electrical test setup included a Desert Cryogenics® TTP6 probe station, an Agilent® N5230A network analyzer, an Agilent® 8562EC Spectrum Analyzer and an Agilent® E8257D PSG Analog Signal Generator. The device under test was directly probed and connected to the measurement instrumentation without the use of any external electronic interface.

A. Transmission Measurements

3rd and 4th order channel-select filters at 94 and 271 MHz were tested. The measurement results are summarized in Table I. The transmission response and photomicrograph of the 3rd order filter at 271 MHz are shown in Fig. 4. Using the equivalent circuit model given in Fig. 3, the equivalent device parameters were extracted by fitting the experimental data. C_0 was estimated from the geometrical parameters of the resonator using Equation (1), and then the parasitic components (R_{p1}, C_{p1}, R_{p2} and C_{p2}) are extracted from the *S*-parameter data by subtracting C_0. Given the smaller amount of silicon present in the coupling regions, we assume that R_{p2} and C_{p2} are related to R_{p1} and C_{p1} by a scaling factor s, so that:

$$R_{p2} = R_{p1}/s, \qquad C_{p2} = C_{p1}\cdot s \qquad (5)$$

This assumption proves correct when the extracted parameters are fitted to the experimental results as shown in Fig. 4 (a).

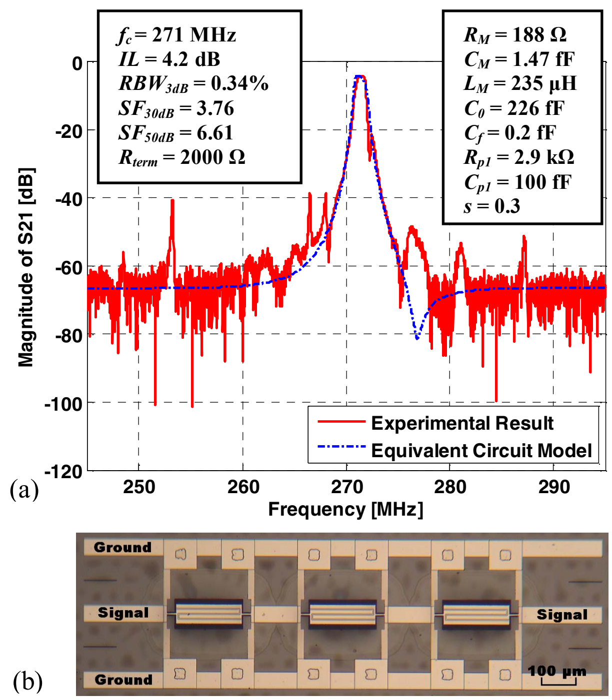

Fig. 4. (a) Transmission response and (b) photomicrograph of the 271 MHz 3rd order filter.

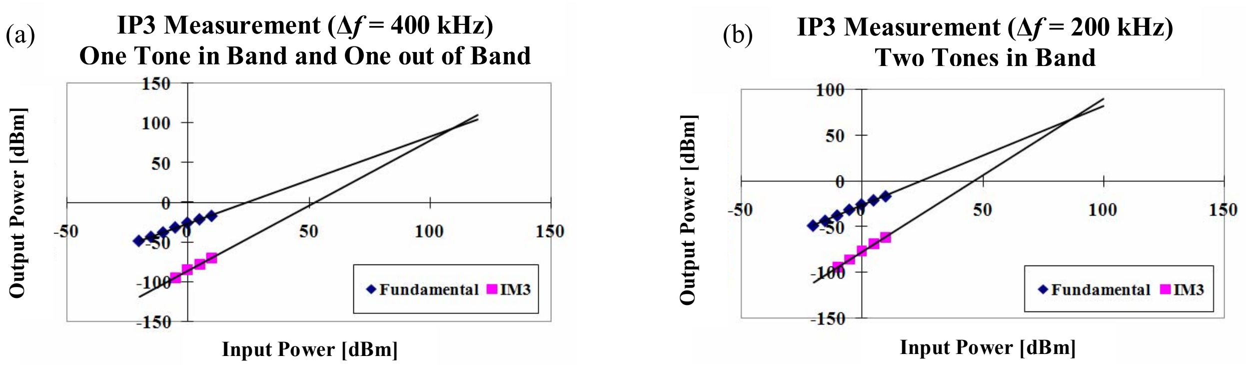

Fig. 5. (a) IP3 measurement data for the case in which one input signal is in band and the other out of band. IIP3 of 110 dBm was recorded. (b) IP3 measurement data when both input signals are in band. IIP3 of 88 dBm was recorded.

Using those fitting parameters and Equations (2)-(4), the *IL*, *Rej.*, and RBW_{3dB} are calculated to be 1.7 dB, 59 dB, and 0.49%, respectively. As we can see, the *IL* and *BW* values deviate a lot from the experimental data, which means parasitic components play an important role in the filter's performance. On the other hand, because Equations (2)-(4) were derived based on a series of approximations, a more accurate analysis was performed to study the effect of parasitics. We found that the *IL* would become 1.9 dB and the RBW_{3dB} would be increased to 0.42%, if all the parasitic components were removed. Therefore filter performance can be improved to a large extent by eliminating substrate parasitics, although the most effective way to lower *IL* is to boost the quality factor of the AlN contour-mode resonators.

B. Nonlinearty Measurements

Two nonlinearity characteristics of the 3rd order 271 MHz filter have been measured: the 1 dB compression point, which was recorded to be 10 dBm, and the third-order intercept point (IP3). For the IP3 measurement, a two-tone test technique [8] was used. Two interferers (at f_1 and f_2) were selected to generate a 3rd order intermodulation (IM3) component at the filter center frequency (f_c). The frequencies of the two interferers are:

$$f_1 = f_c - 2\cdot\Delta f\ , \qquad f_2 = f_c - \Delta f \tag{6}$$

If we use the 3 dB bandwidth of the filter as a reference, depending on the value of Δf, the two interferers can be selected to be both outside the pass band, one within the pass band and one not, or both within the pass band.

For the 3rd order 271 MHz filter, the center frequency f_c was at 271.41 MHz and the 3 dB bandwidth was 920 kHz. We have conducted IP3 measurements on all the three possible cases. When both the interferers are out of the 3 dB band, no IM3 product was measured above the noise floor of the spectrum analyzer (-100 dBm). In the second case, we chose Δf to be 400 kHz (f_2 in band while f_1 outside); the input third intercept point (*IIP3*) was measured to be 110 dBm. In the third case, we chose Δf to be 200 kHz (both f_1 and f_2 in band); the *IIP3* was recorded to be 88 dBm. The experimental data are presented in Fig. 5. This filter design shows excellent performance in terms of immunity to intermodulation distortions. The *IIP3* values are comparable to existing SAW devices [9] and superior to any similar electrostatically-transduced micromechanical device.

IV. CONCLUSION

For the first time, two-port piezoelectric AlN contour-mode resonators have been connected in series and coupled using their intrinsic capacitance to form multi-frequency, narrow bandwidth, low insertion loss, high off-band rejection and extremely linear channel-select filters. Single-chip multi-band RF solutions can be envisioned in the near future based on this technology. On-going research is aimed at lowering the termination impedance of the filters, as well as expanding this coupling technique to GHz frequencies.

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