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Very high frequency channel-select MEMS filters based on self-coupled piezoelectric AlN contour-mode resonators

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ABSTRACT

This paper reports experimental results on single-chip multi-frequency channel-select filters based on self-coupled piezoelectric aluminum nitride (AlN) contour-mode microelectromechanical (MEMS) resonators. Two-port AlN contour-mode resonators are connected in series and electrically coupled using their intrinsic capacitance to realize multi-frequency (94–271 MHz), narrow bandwidth (∼0.2%), low insertion loss (∼2.3 dB), high off-band rejection (∼60 dB) and high linearity (IIP3 ∼100 dBmV) channel-select filters on the same chip. This technology enables multi-frequency, high-performance and small-form-factor filter arrays and makes a single-chip multi-band reconfigurable radio frequency (RF) solution possible in the near future.

1. 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 (∼10 MHz up to few GHz) 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 technique to design integrated, high-performance and narrow-band filters is based on high quality factor (Q) microelectromechanical (MEMS) resonators. Several research groups have been developing MEMS resonator technologies based on electrostatic [1–3] and piezoelectric [4,5] transduction mechanisms that are capable of providing multiple frequencies of operation on the same silicon substrate, in contrast with conventional Film Bulk Acoustic Resonator (FBAR) or quartz crystal technologies for which only one frequency per substrate is possible. Among these, aluminum nitride (AlN) contour-mode vibrating RF MEMS technology [4] stands out as the most promising one 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 (1000–4000) and low motional resistance (25–700 Ω), which makes the devices readily matched to conventional 50 Ω RF systems. Compared with Silicon-based electrostatic MEMS resonators, a significant advantage of piezoelectric transduction is that low motional resistance and high power handling can be achieved simultaneously, while the motional resistance of electrostatic MEMS resonators is generally much larger due to the relatively lower electromechanical coupling coefficient. Among all the available piezoelectric materials (e.g., PZT and ZnO), AlN is the only material that has been proven post-CMOS compatible and widely used in the wireless communication industry (FBAR filters as duplexers for cell phones [6]). Additionally, among the other piezoelectric materials, thin-film AlN has shown some of the highest $k_t^2 Q$ products (figure of merit of a mechanical resonator; k_t^2 is the effective electromechanical coupling coefficient) making it one of the preferred candidates for filter synthesis based on laterally vibrating MEMS resonators.

Employing this piezoelectric AlN contour-mode MEMS technology, very high frequency (VHF) band-pass filters have been demonstrated by electrically coupling one-port resonators in a ladder topology [7]. The implementation of ladder filters requires the ability to fabricate resonators with different resonant frequencies for the series and shunt branches. Depending on the bandwidth

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specification, a ladder filter may require a relative frequency shift ($\Delta f/f_s$) ranging between 0.1% and 3% in the resonator series resonant frequency, which poses a big challenge on the ultimate achievable yield. Furthermore, in [7] the off-band rejection was measured to be only 27 dB, which can cause severe limitations for channel-select applications. In this work, we propose a new topology to implement multi-frequency (94–271 MHz) channel-select RF MEMS filters with narrow bandwidth (~0.2%), low insertion loss (~2.3 dB), and high off-band rejection (~60 dB) [8]. Three or four two-port AlN contour-mode resonators are connected in series and coupled electrically by their intrinsic capacitance to form high-performance 3rd and 4th order filters, respectively. Compared to the classical ladder filter implementation, this coupling technique reduces the overall device size by employing only half components, improves manufacturing yield by using single-frequency resonators, intrinsically provides narrower bandwidth for channel selection, and, easily increases filter off-band rejection without the need to resort to different size resonators.

2. Resonator and filter design

2.1. Design goals

For the application of channel selection, there are specific design goals that need to be met to synthesize filters based on piezoelectric AlN contour-mode MEMS resonators. First of all, the fractional bandwidth (*FBW*), namely the filter 3 dB bandwidth ($BW_{3\,\mathrm{dB}}$) divided by the center frequency (f_c), has to be small enough to really select the desired RF signal channel with very good rejection of adjacent channels. The specifications may vary depending on the particular wireless communication standard. For example, the channel width of the IEEE 802.11a standard is 16.6 MHz at 5 GHz center frequency; correspondingly the fractional channel bandwidth is 0.3% [9]. On the other hand, it is also preferable to pursue narrower channels to develop novel RF architectures for which smaller channel bandwidth may result in higher efficiency of electromagnetic spectral utilization and higher signal-to-noise ratio [1].

Second, low insertion loss is very critical for direct channel selection at RF frequencies. For traditional heterodyne and homodyne (direct-conversion) architectures, channel selection is usually performed at the baseband frequency after the low noise amplifier (LNA) and mixer stages, which relaxes the *Q* requirements on the filters. It is also possible to place the channel-select filter before the mixer, but this is done at the cost of increasing the RF signal gain (therefore power consumption) of the LNA [9]. In all these cases, insertion loss is not a significant issue, since the signal is already amplified before it goes through the channel selector. However, if direct RF channel selection and filtering are carried out before the LNA stage, insertion loss of the channel-select filter becomes the most critical parameter in the receiver chain, since solely 1 dB degradation of the RF signal may result in extra burden on the subsequent stages (LNA, mixer, local oscillator, etc.) in terms of gain, noise figure, and linearity. In order to satisfy the same receiver specification, orders of magnitude more power consumption or chip area occupation may be required to account for the power loss in the first stage. Therefore, the insertion loss of an RF channel-select filter has to be as small as possible.

Finally, the RF channel-select filter should also serve as a bridge to connect the antenna with the transceiver integrated circuits (ICs). Antennas generally have a characteristic impedance around 50 Ω, while transceiver ICs usually work at a higher impedance. Therefore, it is desirable for the channel-select filter to have low device impedance ranging from 50 Ω to several kΩ, so that impedance matching is realized through the filter itself and extra power loss in external matching networks is avoided.

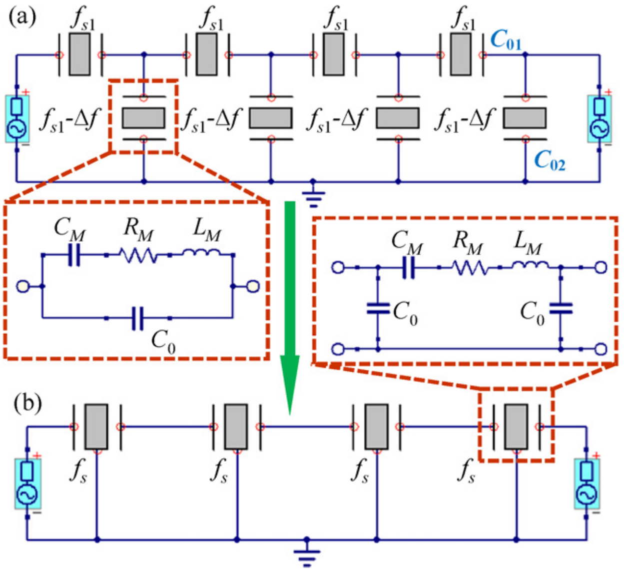

Fig. 1. Equivalent circuit schematics of (a) the ladder topology and (b) the self-coupling technique for the synthesis of a 4th order band-pass filter. The Butterworth Van Dyke (BVD) models for the composing one-port and two-port piezoelectric AlN contour-mode resonators are also given.

These specifications are valid in general and apply also to the VHF filters of this work. Although the demonstrated filters operate in a frequency range below the more conventional cell bands, they can still be employed in lower frequency systems such as TV tuners or as intermediate frequency (IF) stages in heterodyne receivers so as to solve the problem of tuning high-*Q* systems by means of filter banks as proposed by Bakkaloglu and co-workers in [10].

2.2. From ladder to self-coupling topology

The ladder topology has been widely used in electrically coupled filters, e.g., FBAR duplexers [11], electrostatically [12] as well as piezoelectrically [7] transduced band-pass MEMS filters. For an nth order filter, $2n$ one-port resonators are needed to form the cascaded L networks, as shown in Fig. 1(a). Among these devices, n series resonators have a series resonant frequency at f_{s1} and the other n shunt resonators at $f_{s1} - \Delta f$, so that the series resonance of the series branch, f_{s1}, coincides with the parallel resonance of the shunt branch, f_{p2}. The fractional bandwidth of the final filter can be derived to be approximately $8k_t^2/\pi^2$, primarily determined by the effective electromechanical coupling coefficient, k_t^2, while the out-of-band rejection is set by the transducer capacitance ratio (C_{02}/C_{01}, as shown in Fig. 1 and can be calculated using the equation for $C_{0,1}$ in Eq. (1)) of the resonators in the shunt and series branches [7]. In the piezoelectric AlN contour-mode technology, the desired frequency shift Δf was realized by lithographically removing small amounts of Pt electrodes to reduce the mass loading and raise the resonant frequency. This additional process step introduces an additional complication in the micro-fabrication of the filters and can limit the ultimate achievable yield. Furthermore, the out-of-band rejection was found to be ~27 dB causing severe limitations on channel-select applications.

Therefore, based on all these considerations and the design goals described in the previous section, we propose a self-coupling technique that utilizes the intrinsic capacitance existing in two-port AlN contour-mode resonators, so that high-performance narrow-