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# Hybrid Ultra-Compact 4th Order Band-Pass Filters Based On Piezoelectric AlN Contour-Mode MEMS Resonators

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# Hybrid Ultra-Compact 4th Order Band-Pass Filters Based On Piezoelectric AlN Contour-Mode MEMS Resonators

## Abstract

This work reports on the design, fabrication and testing of a new class of hybrid (filter design using combined electrical and mechanical coupling techniques) ultra-compact (800×120 μm) 4th order band-pass filters based on piezoelectric Aluminum Nitride (AlN) contour-mode microelectromechanical (MEM) resonators. The demonstrated 110 MHz filter shows a low insertion loss of 5.2 dB in air, a high out-of-band rejection of 65 dB, a fractional bandwidth as high as 1.14% (hard to obtain when only conventional electrical coupling is used in the AlN contour-mode technology), and unprecedented 30 dB and 50 dB shape factors of 1.93 and 2.36, respectively. All these are achieved in an extremely small footprint and by using just half the space that any other 4th order filter would have taken. In terms of nonlinearities, the 110 MHz filter shows a 1 dB compression point higher than +63 dBmV and input third order intercept point (IIP3) values well beyond +153 dBmV. This new hybrid design represents a net improvement over the state of the art and constitutes a very promising solution for intermediate frequency (IF) filtering in many wireless communication systems.

## Keywords

Hybrid, Band-Pass Filter, Piezoelectric, AlN Contour-Mode Resonator, MEMS

## Disciplines

Electrical and Electronics

## Comments

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# HYBRID ULTRA-COMPACT 4TH ORDER BAND-PASS FILTERS BASED ON PIEZOELECTRIC ALN CONTOUR-MODE MEMS RESONATORS

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## ABSTRACT

This work reports on the design, fabrication and testing of a new class of hybrid (filter design using combined electrical and mechanical coupling techniques) ultra-compact (800×120 μm) 4th order band-pass filters based on piezoelectric Aluminum Nitride (AlN) contour-mode microelectromechanical (MEM) resonators. The demonstrated 110 MHz filter shows a low insertion loss of 5.2 dB in air, a high out-of-band rejection of 65 dB, a fractional bandwidth as high as 1.14% (hard to obtain when only conventional electrical coupling is used in the AlN contour-mode technology), and unprecedented 30 dB and 50 dB shape factors of 1.93 and 2.36, respectively. All these are achieved in an extremely small footprint and by using just half the space that any other 4th order filter would have taken. In terms of nonlinearities, the 110 MHz filter shows a 1 dB compression point higher than +63 dBmV and input third order intercept point ($IIP_3$) values well beyond +153 dBmV. This new hybrid design represents a net improvement over the state of the art and constitutes a very promising solution for intermediate frequency (IF) filtering in many wireless communication systems.

## INTRODUCTION

To further reduce the fabrication cost and form factor of personal telecommunication systems, there have been tremendous efforts in both academia and industry to realize fully integrated CMOS radio frequency (RF) solutions using low-IF and zero-IF radio architectures [1]. However, due to the lack of high quality factor ($Q$) filtering components, which used to be implemented by off-chip quartz crystal and Surface Acoustic Wave (SAW) devices, homodyne architectures generally have poorer sensitivity, image rejection and dynamic range than superheterodyne transceivers. These issues lead to look at alternative ways of developing post-CMOS compatible high-$Q$ MEMS resonators that enable low cost and small footprint IF and RF filtering and, most importantly, improve flexibility in defining multi-frequency and multi-band RF architectures.

Several research groups have been developing MEMS resonator technologies based on electrostatic [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, the aluminum nitride (AlN) contour-mode RF MEMS technology [4] stands out as one of the most promising and 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 devices readily matched to conventional 50 Ω RF systems.

Based on this new AlN contour-mode MEMS technology, VHF band-pass filters have been demonstrated using electrical [5, 6] and mechanical coupling [7, 8] techniques. For electrical coupling, several AlN contour-mode resonators are cascaded in a ladder or self-coupling topology to realize higher order filtering. The fractional bandwidth of these filters is generally set by the

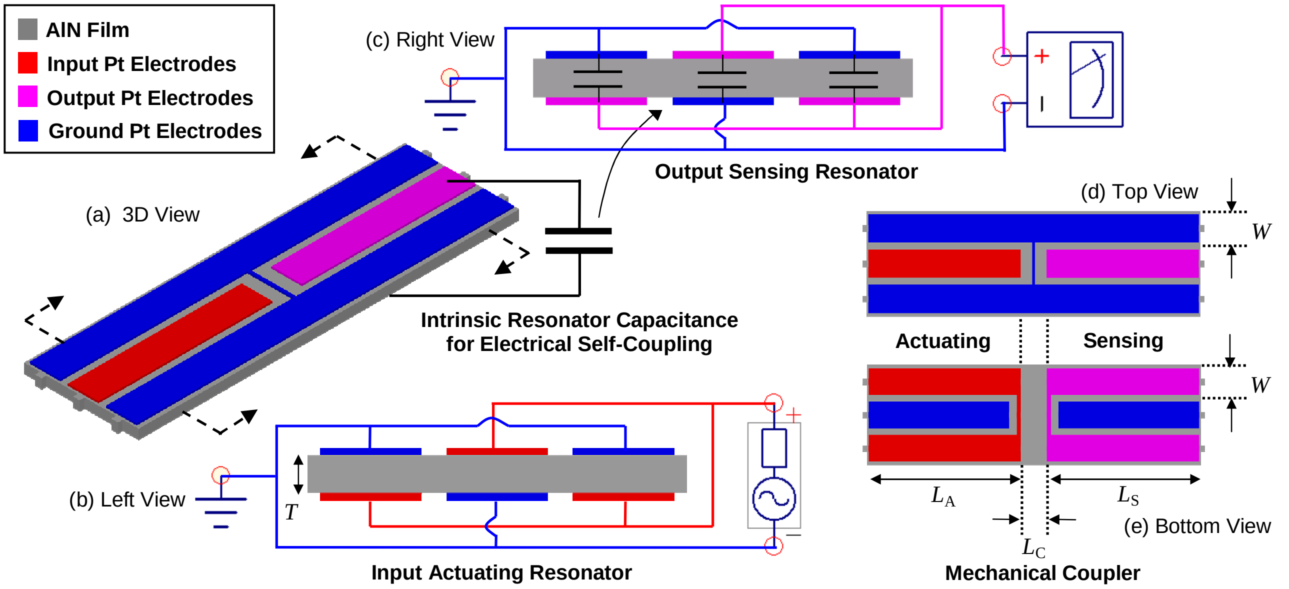

***Fig. 1:*** *(a) 3D, (b) left, (c) right, (d) top and (e) bottom schematic views of the 2nd order sub-filter stage. It consists of an input actuating AlN contour-mode piezoelectric resonator, an output sensing resonator and a rectangular mechanical coupler in between with lengths of $L_A$, $L_S$ and $L_C$, respectively. W is the finger width which determines the resonant frequency of the resonators and therefore the center frequency of the filter, while T is the AlN film thickness. All $L_A$, $L_S$, $L_C$ and W values can be defined by photolithography, which enhances designer's freedom in setting filter center frequency (W), bandwidth ($L_C$/W) and termination ($L_A$ and $L_S$) independently.*

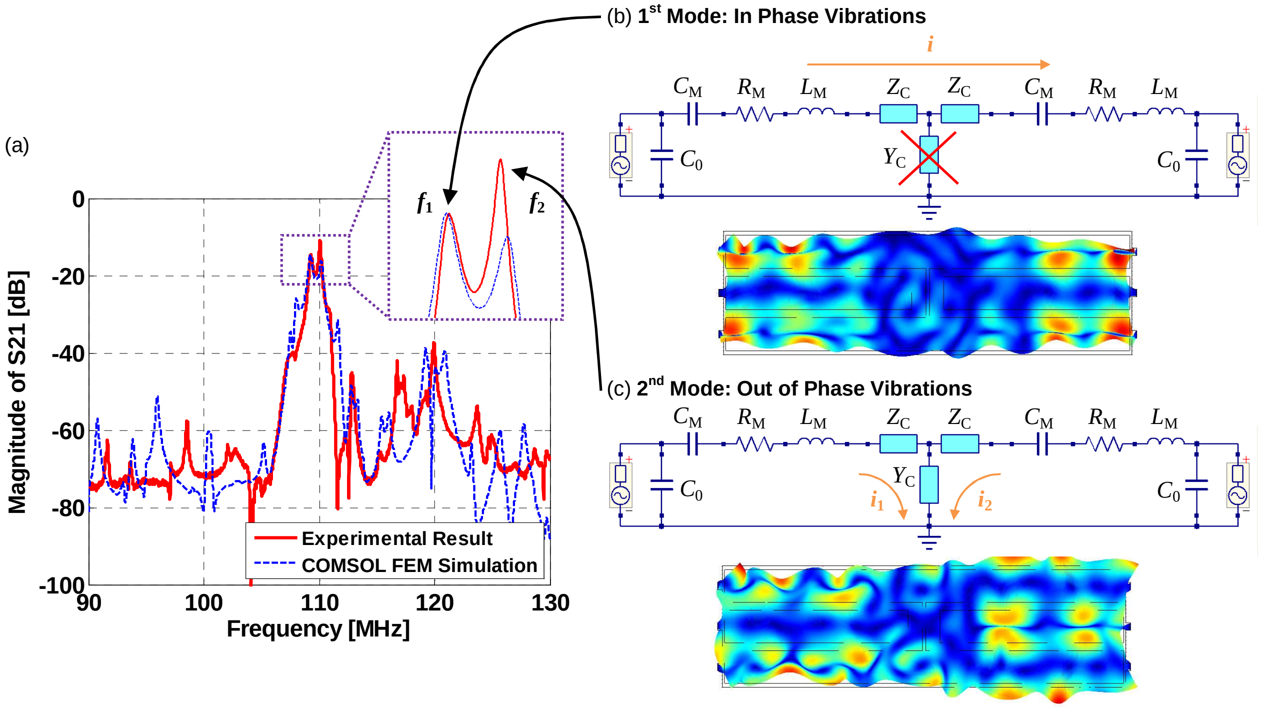

***Fig. 2:*** *(a) Unmatched transmission ($S_{21}$ at 50 Ω termination) curves are given for the mechanically coupled 2nd order sub-filter stage. The curves show a good agreement between the experimental data and the COMSOL® FEM simulation (discrepancies likely due to theoretically unpredictable Q values for different vibration modes). Two transmission peaks can be seen: (b) for the first peak, the output resonator is vibrating in phase with the input one; (c) for the second peak, the two resonators are moving out of phase. The equivalent circuits are also given to illustrate the function of the mechanical coupler.*

effective electromechanical coupling coefficient $k_t^2$, which is a material property and limits the bandwidth to be 0.2% to 1% in the AlN contour-mode technology. Both mechanical coupling and dual mode techniques can be adopted to increase the bandwidth to a certain extent, as shown in [7–9]. However, the pass band shape and spurious modes are very difficult to control when the filter order is higher than 2. Therefore, with this work we propose a new hybrid solution that takes advantage of both electrical and mechanical coupling techniques to implement small form factor, high order and spurious free filtering functions. The demonstrated 110 MHz filter shows a low insertion loss of 5.2 dB in air, a high out-of-band rejection greater than 65 dB, a fractional bandwidth as high as 1.14% (hard to achieve when only conventional electrical coupling is used), and unprecedented 30 dB and 50 dB shape factors of 1.93 and 2.36, respectively. All these are achieved in an extremely small footprint and by using just half the space that any other 4th order filter would have taken.

## FILTER DESIGN

The 4th order hybrid filter consists of two mechanically coupled sub-filter stages electrically cascaded and coupled by the intrinsic capacitance existing in the piezoelectric AlN contour-mode resonators, as illustrated in Fig. 1.

### Mechanical Coupling

Each sub-filter stage can be treated as a 2nd order filter which has a one-port input actuating resonator [10], an output sensing resonator and a passive mechanical coupler in between (Fig. 1). The mechanical coupler is equivalent to an electrical T-network which includes two series components with impedance $Z_C$ and a parallel component with admittance $Y_C$ (Fig. 2) [7]. Both the values of $Z_C$ and $Y_C$ can be capacitive or inductive depending on the geometrical dimensions of the mechanical coupler. The 2nd order system has two modes of mechanical vibration, as explained by the equivalent circuits of Fig. 2. In the first mode, the input and output resonators vibrate in phase with each other and the coupling element $Y_C$ has no effect on the first system resonance at $f_1$. In the second mode, the two resonators vibrate out of phase and the coupling admittance $Y_C$ can be equally split into input and output branches causing a higher system resonance at $f_2$. The frequency separation between $f_1$ and $f_2$ is primarily set by the value of $Y_C$, and the filter bandwidth can then be engineered at the CAD layout level by defining the coupler dimension, $L_C$, through photolithography. All this analysis has been verified by COMSOL® FEM simulations, which indicate that the fractional bandwidth can be varied from 1% to 2% by designing the length to half wavelength ($W=\lambda/2$) ratio ($L_C/W$ in Fig. 1) of the mechanical coupler, as shown in Fig. 3.

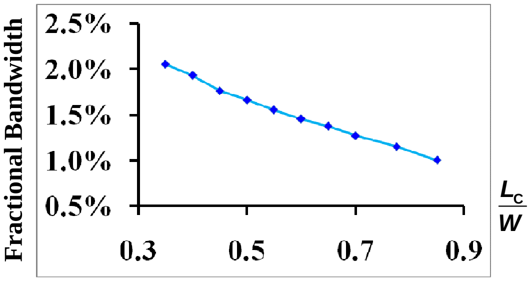

***Fig. 3:*** *Filter fractional bandwidth plotted as a function of the length to half wavelength ratio $L_C/W$, obtained from COMSOL® FEM simulations.*

The unmatched transmission curves ($S_{21}$ at 50 Ω termination) of such a mechanically coupled sub-filter are also given in Fig. 2. They show a good agreement between the experimental result and the COMSOL® FEM simulation that was employed for the design of this filter. Compared with the dual-mode AlN mechanical filters using an annular geometry [8, 9], this new rectangular topology drastically reduces the die space of the single-stage 2nd order filter by eliminating the inevitable empty space present in the annulus. Further, differently from any other mechanically coupled MEMS filter demonstrated to date, this device requires a mechanical coupler whose dimensions are comparable to the acoustic wavelength instead of being a significant fraction of it. Therefore its frequency of operation can be extended to the GHz range.

### Electrical Self-Coupling

This work increases the filter order of any previously demonstrated low-loss and spurious free mechanically coupled filter from a mere 2nd order to a 4th order by electrically coupling two of the mechanically coupled sub-filter stages using the intrinsic capacitance, $C_0$, of the resonators. In this way the first ever hybrid MEMS filter (Fig. 4) has been realized. The principle of electrical coupling is explained in further details in [11]. In the case of AlN contour-mode resonators, the electromechanical transducer itself is an electrical capacitor $C_0$, so that no external coupling element is needed for the electrical coupling of two sub-filter stages. This electrical self-coupling technique can improve manufacturing yield by employing single-frequency resonators for filter synthesis [6] and reduce the overall device size by eliminating external coupling elements. As we can see from Fig. 4, a much cleaner filter response is obtained after electrical coupling. Shape factors are almost halved and out-of-band rejection is improved from 50 to 65 dB. All these are achieved in a small silicon area of just 800×120 μm.

## EXPERIMENTAL RESULTS

The filters were fabricated using a simple five-mask, low-temperature, potentially post-CMOS compatible process [3]. The two Pt electrode 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 1.4˚. An additional electroplated Au layer was finally added on top of the routing electrodes to reduce the electrical resistance of the pads. The electrical test setup included a Desert Cryogenics® TTP6 probe station, an Agilent® N5230A network analyzer (for 2 port S-Parameter measurements), an Agilent® 8562EC Spectrum Analyzer and an Agilent® E8257D PSG Analog Signal Generator (for power handling and intermodulation distortion measurements). The devices under test were directly probed and connected to the measurement instrumentation without the use of any external electronic interface.

The measured transmission response for a 110 MHz hybrid 4th

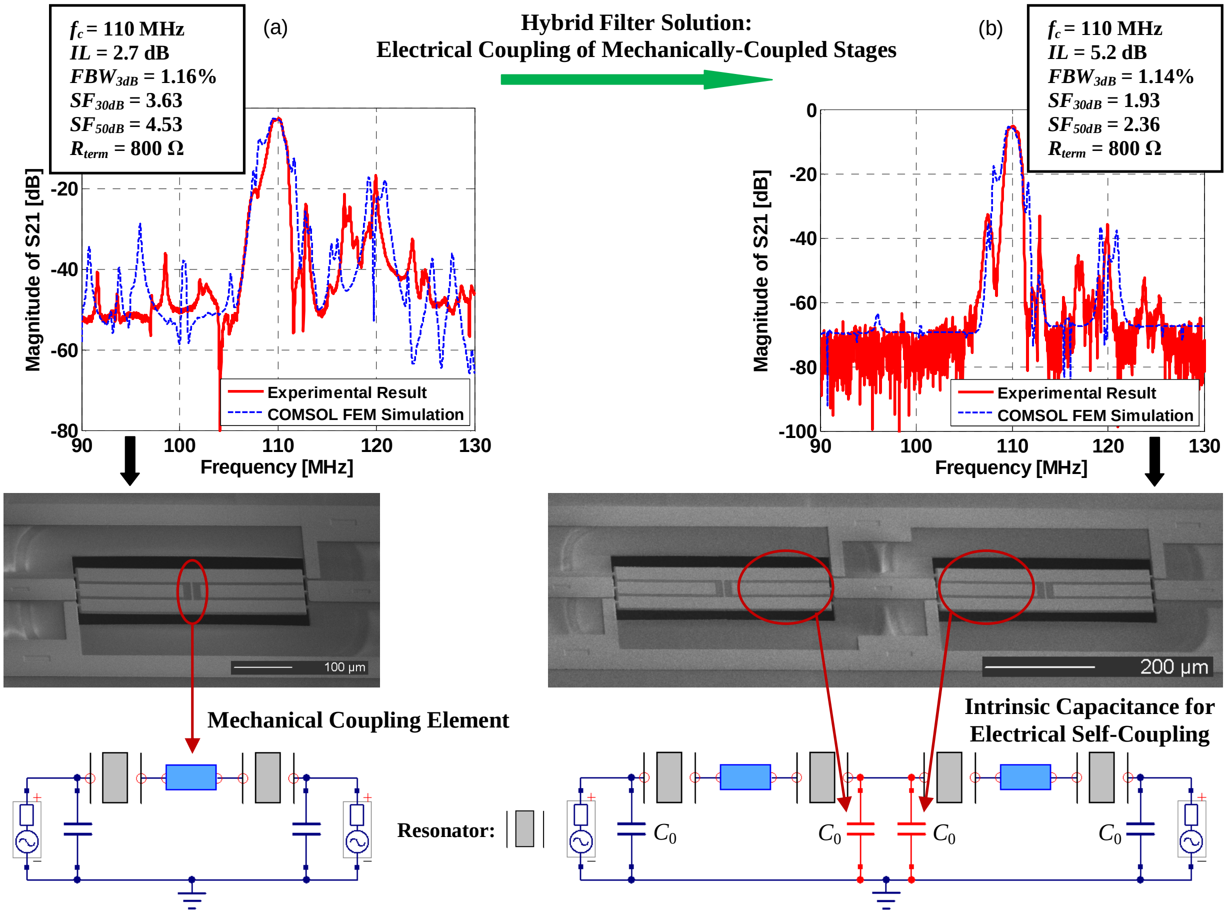

***Fig. 4:*** *(a) Transmission response ($S_{21}$ at 800 Ω termination) and SEM picture (below) of the single-stage mechanically coupled 2nd order sub-filter. (b) Transmission response ($S_{21}$ at 800 Ω termination) and SEM picture (below) of the two-stage 4th order filter, which is formed by electrically cascading two single stages and coupling them using the intrinsic capacitance of the AlN contour-mode piezoelectric resonators.*

order filter using 800 Ω termination is show in Fig. 4 (b). The electrical self-coupling technique suppresses most of the spurious modes that appear in the mechanically-coupled single stage (Fig. 4 (a)) by pushing them below the feed-through level. In this way a much cleaner filter response is obtained. The few discrepancies between COMSOL@ simulations and experimental results (evident in the presence of two additional out-of-band peaks) are probably caused by the fact that a $Q$ of 500 was assumed for all the modes of vibration and which is likely not to be the case in reality. A lower $Q$ for spurious modes masks their presence in the final transmission plot of the experimental data. The 4th order filter has a low insertion loss of 5.2 dB in air, a high out-of-band rejection of 65 dB, a fractional bandwidth as high as 1.14%, and especially unprecedented 30 dB and 50 dB shape factors of 1.93 and 2.36, respectively. Simulations also show that the insertion loss can be further improved to 2.6 dB if a $Q$ of 1000 is achieved.

Power handling and nonlinearity characterization were also performed for the same 110 MHz 4th order filter. The results show that a 1 dB compression point higher than +63 dBmV (max allowed by the test set up) can be obtained. Furthermore, a two-tone test technique [12] was used to measure the input third order intercept point ($IIP_3$) values. $IIP_3$ values well beyond +153 dBmV were recorded for all three analyzed cases: (a) both of the two interfering tones are in the pass band; (b) one tone in band and the other out of band; (c) both are out of the pass band. These data show superior performance of this filter design in terms of immunity to intermodulation distortions over other electrically coupled AlN contour-mode devices [6], electrostatically-transduced resonators [12] or SAW counterparts [13].

The temperature coefficient of frequency (TCF) of the filter was measured to be linear in the 300 to 400 K range and equal to -25.7 ppm/K, as shown in Fig. 5.

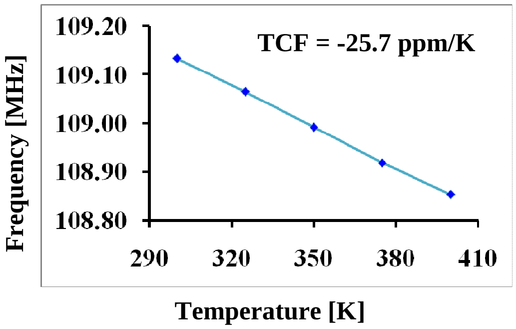

***Fig. 5:*** *Temperature coefficient of frequency (TCF) of the hybrid 4th order filter.*

## CONCLUSION

The first ever hybrid MEMS filter has been designed, fabricated and tested. The device consists of two mechanically coupled sub-filter stages electrically cascaded and coupled by the intrinsic capacitance existing in the piezoelectric AlN contour-mode resonators. The demonstrated 110 MHz filter shows unprecedented rejection, shape factor and bandwidth performances, which would have otherwise not been possible if simply mechanical (pass band shape and spurious modes are hard to control in 3rd or 4th order filters [7]) or electrical (wide bandwidth, sharp roll off and small area are hard to achieve [5, 6]) coupling techniques were to be used. Therefore, this new hybrid design represents a net improvement over the state of the art and constitutes one of the most promising solutions for IF filtering in many wireless communication systems. On-going research is aimed at lowering the filter termination impedance, as well as expanding this coupling technique to GHz frequencies for RF filtering.

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