# A $Pb(Zr_{0.55}Ti_{0.45})O_3$-Transduced Fully Differential Mechanically Coupled Frequency Agile Filter

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***Abstract*—This letter reports on the performances of a frequency-tunable lead-zirconate-titanate-transduced fully differential mechanically coupled high-overtone width-extensional filter. The demonstrated electric field tuning provides channel agility and bandwidth adjustability for the incorporation of analog spectral processors in modern radio receiver architectures. We designed and experimentally characterized the higher overtone frequency response of a fully differential width-extensional filter. The filter demonstrates a center frequency $(f_C)$ tuning range of 7 MHz at 260 MHz and an adjustable bandwidth from 3 to 6.3 MHz while maintaining a maximum frequency shift due to hysteresis effects below 0.14% and a stopband rejection floor of −60 dB.**

***Index Terms*—Differential, filters, piezoelectric, RF MEMS, voltage tuning.**

## I. Introduction

THE forthcoming software-defined radios that have compact dimensions, miniscule weight, low power demands, and robustness to process and temperature variations are greatly desirable. In addition to commercial applications, the U.S. military has been actively developing the Joint Tactical Radio System (JTRS) to work in harmony with existing military and civilian radios. This radio architecture demands the existence of high-performance tunable filters and filter banks to discern signals with dynamic waveforms and bandwidths. A width-extensional mode (WEM) resonator is an excellent constituent resonator to realize these filter banks because it has a high quality factor $(Q)$ and frequency of operation that can be defined lithographically [1]. Furthermore, higher overtone frequency response can be excited by selectively patterning the electrodes of the filter [2].

Dielectrically transduced thickness shear mode filters with analog voltage tunable center frequency and bandwidth [3] and digitally tunable MEMS filter using mechanically coupled resonator array [4] have been previously demonstrated. However, the barriers in frequency design space, bandwidth range, and processing technology have motivated the investigations for a new transducer material that has a large electromechanical coupling coefficient and a frequency-tuning capability. Lead zirconate titanate (PZT) is an appealing transducer material because it has been previously shown to have up to 6% frequency-tuning capabilities [5]. It also exhibits a large electromechanical coupling coefficient ($k_t^2 = 35\%$) in thickness-extensional mode [6]. The maximum percent bandwidth $(BW/f_C)$ of the filter is determined by the $k_t^2$ of the transducer. The large $k_t^2$ of PZT facilitates a filter design with a large percent bandwidth. In our previously reported research, we have fabricated and characterized PZT-transduced contour-mode resonators that demonstrate 5.1% electric-field-dependent frequency-tuning capability [7]. A bandpass filter with a small footprint, tunable bandwidth, and center frequency agility can be realized by coupling PZT-transduced contour-mode resonators mechanically.

An excellent stopband rejection is a very desirable property in modern radio transceivers. A closely packed dense array of MEMS filters on the same chip introduces large feedthrough capacitance between the drive and sense electrodes, leading to poor stopband rejection of the filter. The fully differential filter configuration cancels the feedthrough capacitance and improves the stopband floor of the filter [8].

## II. Fully Differential High-Overtone Mechanically Coupled Width-Extensional Filter

The resonant frequency of vibration for contour-mode resonators and filters is defined by lithography. Therefore, contour-mode filters are preferred for realizing multiband and multifrequency filters on a single chip [9]. The bulk-extensional mode resonance of a WEM resonator depends on $W$, with a frequency of operation $(f_C)$ given by

$$f_C = \frac{n}{2W}\sqrt{\frac{E}{\rho}} \tag{1}$$

where $W$ is the width of the resonator, $E$ and $\rho$ are the effective elastic modulus for 2-D expansion and density of the resonator, respectively, and $n$ is the harmonic order. The higher frequency overtone modes of the WEM resonators are selectively excited by patterning electrodes in differential interdigitated configuration on top of the resonator [8].

Mechanically coupled devices demand smaller area since the coupling spring is small. Furthermore, they do not require extra device area to implement a differential configuration due to inherent mechanical inversion available through the resonators [10]. To realize a two-pole mechanically coupled filter, two resonators are coupled using a suspension spring, as shown in

Manuscript received July 23, 2009. First published November 3, 2009; current version published November 20, 2009.

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Digital Object Identifier 10.1109/LED.2009.2034112

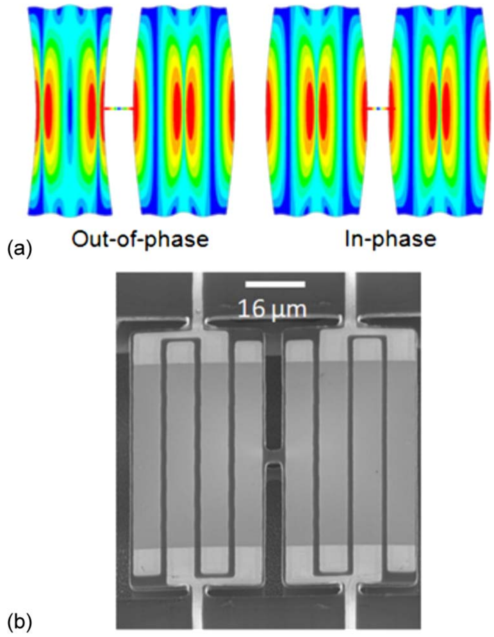


Fig. 1. (a) ANSYS modal analysis showing in-phase and out-of-phase modes of vibrations of a mechanically coupled high-overtone width-extensional filter. (b) SEM image of a PZT-transduced high-overtone mechanically coupled width-extensional filter with differential electrodes.

Fig. 1. The length of the coupling spring is designed to be a quarter acoustic-wavelength long to minimize mass loading of the resonators. The width of the coupling spring then defines the stiffness of the coupling spring. The bandwidth $(BW)$ of such a mechanically coupled filter is given by

$$BW = \frac{f_C}{k_{ij}} \frac{k_s}{k_r} \tag{2}$$

where $f_C$ is the resonant frequency, $k_s$ and $k_r$ are the spring stiffness of the coupling spring and resonator, respectively, and $k_{ij}$ is the filter coefficient [11]. Fig. 1(a) shows the in-phase and out-of-phase high-overtone modes of a width-extensional filter simulated in ANSYS. Device fabrication is the same as reported in [7]. The SEM image of a PZT-transduced two-pole fully differential mechanically coupled high-overtone width-extensional filter fabricated in this process is shown in Fig. 1(b).

## III. Measurements of a Two-Pole Fully Differential Mechanically Coupled Filter

We characterized the two-pole fully differential mechanically coupled filter using the measurement setup shown in Fig. 2. The fully differential configuration enables us to cancel feedthrough capacitances between drive and sense electrodes, thereby improving the stopband floor of the filter. The filter was characterized on a Cascade microwave probe station using GSGSG probes and a two-port Agilent E8364B network analyzer. The dc bias is superimposed to the ac signal at both input and output ports using $bias - Ts$ for all measurements. Fig. 3 shows the differential filter response as the electric field tuning biases are applied to the electrodes. The wide frequency measurement was performed, and all other harmonic modes of vibrations are strongly attenuated by at least 30 dB below the designed

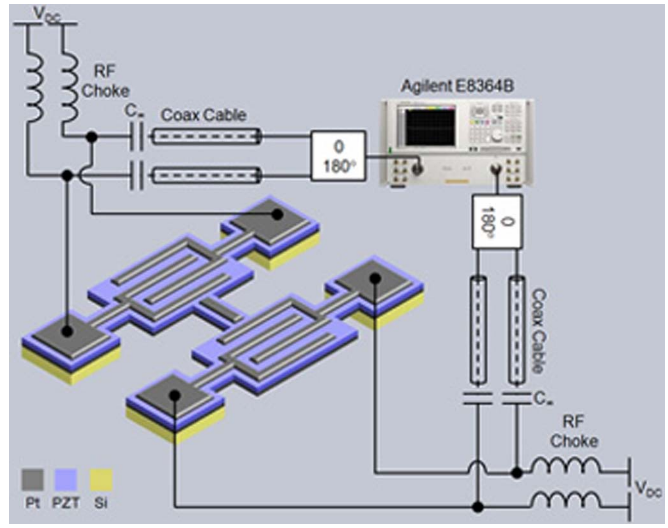


Fig. 2. Testing configuration for a two-pole mechanically coupled high-overtone fully differential filter.

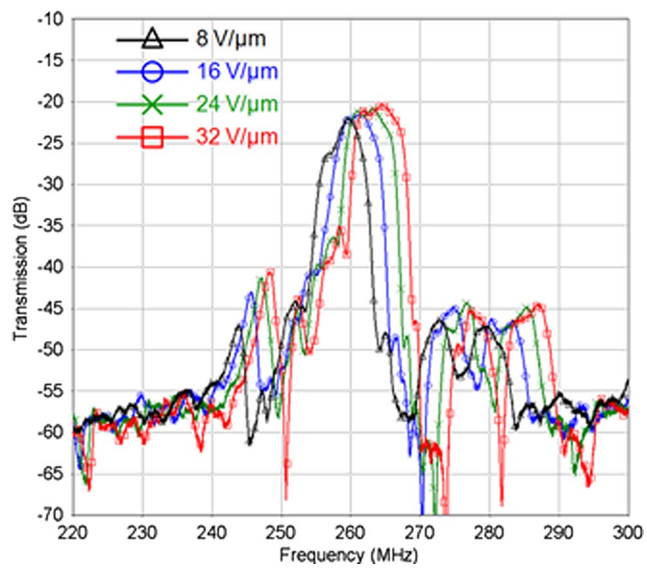


Fig. 3. Measured transmission of a PZT-transduced two-pole high-overtone WEM filter with electric field tuning. Input and output terminals were terminated with 50-Ω termination impedance $(R_L)$ for all measurements.

frequency of operation. The electric field not only improves the piezoelectric coupling coefficient (via poling of the ferroelectric domains) but also increases the Young's modulus of the PZT film [7]. The increase in Young's modulus of the PZT film increases the effective acoustic velocity of the constituent resonators, thereby increasing the center frequency of the filter. The result is up to 3% increase in filter center frequency for a 32-V/$\mu$m applied electric field, which is the highest tuning range reported by any piezoelectrically transduced contour-mode filters to date. In addition, the applied electric field also increases the ratio of $k_s$ to $k_r$, thereby providing up to 100% bandwidth tuning capability for a 32-V/$\mu$m applied electric field. The measured transmission response of a PZT-transduced two-pole high-overtone width-extensional filter with an electric field tuning of 8 to 32 V/$\mu$m in 8 V/$\mu$m increment step in air at room temperature is tabulated in Table I. The center frequency

TABLE I
MEASURED FREQUENCY RESPONSE OF A PZT-TRANSDUCED HIGH-OVERTONE WEM FILTER

| Electric Field (V/$\mu$m) | 8 | 16 | 24 | 32 |
|---|---|---|---|---|
| $IL$ (dB) | $-22.4$ | $-21.5$ | $-21.3$ | $-20.7$ |
| 3dB $BW$ (MHz) | 3.03 | 3.9 | 5.5 | 6.3 |
| $f_C$ (MHz) | 259.1 | 260.5 | 262.3 | 264.2 |
| Stop-band rejection (dB) | 37.6 | 38.5 | 38.7 | 39.3 |

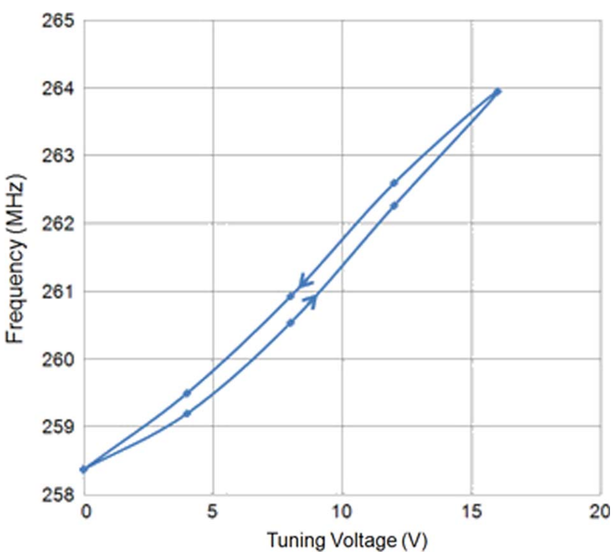


Fig. 4. Measured frequency shifts in PZT-transduced high-overtone width-extensional filter due to hysteresis effect in PZT. A maximum frequency shift of 0.14% was recorded.

and bandwidth tuning features demonstrated by this class of filter could eliminate the necessity of multiple filter and switch networks in radio architecture [12].

The hysteresis effect of PZT may cause the filter to experience undesirable center frequency shifts. We characterized the hysteresis effect on the filter by applying increasing and decreasing electric fields across the PZT thin film. A maximum frequency shift of 0.14% was recorded, as shown in Fig. 4.

Filters with high insensitivity to temperature variations are highly desirable. Temperature characterization was performed by placing the filter on the Cascade probe station with a temperature control stage. Frequency responses were recorded while the device was cooled down to $-20$ °C and heated up to 100 °C. The filter with different dc bias voltages was characterized over the whole temperature range of operation, and it exhibits a temperature coefficient of frequency between $-16$ and $-21$ ppm/°C. These values are comparable to AlN-transduced resonators and filters and quartz crystals used in timekeeping applications for handsets [1].

## IV. CONCLUSION

In conclusion, a PZT-transduced fully differential mechanically coupled filter has shown a large center frequency and bandwidth tuning range. These tuning features have never been demonstrated by any piezoelectrically transduced contour-mode filters reported to date. The fully differential configuration eliminates the feedthrough capacitances between drive and sense electrodes, thereby improving the stopband rejection floor of the transmission. The filter demonstrates excellent robustness to hysteresis due to electric-field-dependent frequency-tuning capability. These features satisfy the filter specifications in JTRS to handle multiple waveforms, eliminate out-of-channel interferers, and substantially decrease the number of filters in the next-generation radios.

## ACKNOWLEDGMENT

The authors would like to thank B. Power, J. Martin, and R. Piekarz of the Army Research Laboratory for their assistance in the fabrication of the filters.

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