Intrinsically Switchable Ferroelectric BST Bulk Acoustic Wave Devices

Milad Zolfagharloo Koohi and Amir Mortazawi
University of Michigan, Ann Arbor, MI, USA

Abstract — **Reconfigurable frequency selective components are essential to reduce the complexity and cost of agile radios. A summary of reconfigurable bulk acoustic wave resonators based on multilayer ferroelectric barium strontium titanate (BST) is presented in this report. First, mode-switchable ferroelectric thin film bulk acoustic wave resonators (FBARs) are presented. Such resonators operate based on a dynamic non-uniform effective piezoelectricity in composite multilayer ferroelectrics with large electrostriction coefficients, like BST. Harmonic resonance modes (nf_o) of a multilayer ferroelectric bulk acoustic wave resonator can be selectively excited with an electromechanical coupling coefficient (K_{eff}^2) equal to the fundament mode, which is contrary to the trend $K_{eff}^2 \propto 1/n^2$ exhibited by conventional piezoelectric bulk acoustic wave resonators. In the second part, an intrinsically switchable BST stacked crystal filter is demonstrated for the first time.**

***Keywords* — Barium strontium titanate (BST), bulk acoustic wave (BAW) filters, stacked crystal filter (SCF), ferroelectrics, ladder-type filter, reconfigurable systems, switchable.**

I. Introduction

With the advent of 5G, the complexity and cost of RF front-ends are dramatically growing, and frequency band proliferation is the biggest contributor to this challenge. Frequency selective components in RF transceivers are primarily acoustic filters. These filters are accompanied with switches to select the desired frequency and mode of operation in mobile devices. However, the incremental addition of these filters and switches to the RF modules are the main drivers for the rising complexity and cost of the transceivers. The number of filters in mobile phones is expected to be more than 100 by the year 2022, contributing to 80% of the entire cost of the RF front-end.

As a possible approach to simplify the future generations of transceivers, we propose to replace the traditional filters with frequency reconfigurable filters. An example of such devices is the intrinsically switchable acoustic filter based on ferroelectrics. Such a device combines the filtering and switching functionality onto a single component by employing the electrostriction effect in ferroelectric thin films like barium strontium titanate (BST). Therefore, ferroelectric filters eliminate the necessity for external switches and can potentially reduce the complexity and cost of RF modules. We have previously reported ladder-type BST thin film bulk acoustic resonator (FBAR) filters and filter banks for the 2 GHz band.

In this work, intrinsically switchable ferroelectric bulk acoustic wave membrane-type filters for frequencies beyond the 2 GHz band are investigated for the first time, and experimental results are presented. A novel mode switchable resonator technology based on multi-layer BST structure has been developed for selective operation across multiple frequency bands. Also, a stacked crystal filter (SCF) based on ferroelectric BST is designed and fabricated for the 3.6 GHz band.

II. Mode Switchable Resonators

Switched-mode BAW resonators are constructed by depositing multiple layers of ferroelectric BST sandwiched between thin-film electrodes, as shown in Fig. 1(a), and enable the design of reconfigurable multiband RF filters [1]. Switched-mode resonators selectively operate at various resonant modes, as shown in Fig. 1 (b), without affecting the electromechanical coupling coefficient. This is accomplished by exploiting the electric-field-induced piezoelectricity and negative piezoelectricity in multilayer BST [2]. Each specific eigenmode can be excited by controlling the sign and magnitude of the effective piezoelectric coefficient of BST layers by applying an appropriate set of dc bias voltages (e.g., Fig 1 (c) represents the required pattern of the piezoelectric coefficient for excitation of mode 2 in a six-layer switched-mode resonator.) Programmable band-switching filters can be designed based on such switched-mode FBARs.

We have experimentally demonstrated a dual-resonance, switched-mode ferroelectric FBAR [1], [2], where the resonator is constructed by employing two BST layers sandwiched between electrodes, as shown in Figure 2(a). The device can selectively resonate at its fundamental mode in the 2-GHz band

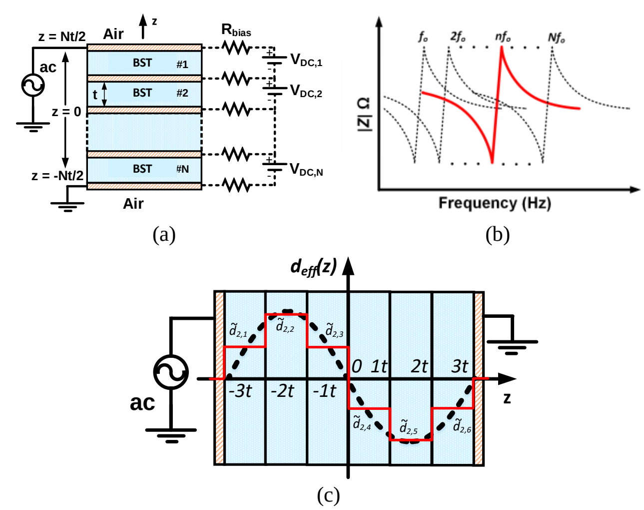

Fig 1. Multi-layer ferroelectric resonator (a) structure and (b) magnitude of the impedance for different states of the device. (c) Example: ideal non-uniform pattern of effective piezoelectric coefficient for selective excitation of only mode 2 in a 6-layer ferroelectric bulk acoustic wave resonator (dashed). The stepwise solidline is the actual realization of such pattern. Piezoelectric coefficient in the last three layers is negative. Piezoelectricity in each BST layer is a function of the magnitude and polarity of the applied DC bias voltage [2].

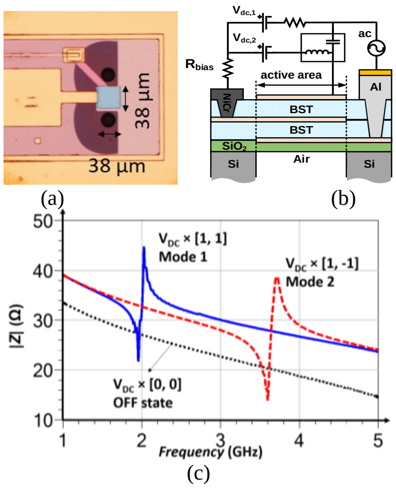

Fig. 2. (a) A photograph and (b) the cross-sectional view of a bilayer BST FBAR as well as (c) the magnitude of the measured electrical impedance for mode 1, mode 2, and the OFF state response.

(mode 1) or its second eigenmode in the 3.6-GHz band (mode 2).). A cross-sectional view of the fabricated device and its dc bias voltage configuration is shown in Figure 2(a) and the photograph of the resonator as well as its impedance response are provided in Figure 2(b) and (c), respectively. When either of the modes is selected by applying their corresponding set of dc bias voltages, the other mode is fully suppressed, as shown in this figure. The device is switched off when the dc bias is removed.

III. Stacked Crystal Filter

The intrinsically switchable stacked crystal filter unit cell contains two BST transducers stacked on top of each other, forming a single membrane-type acoustic resonator. The input transducer drives the resonator at its resonance frequency, while the acoustic energy is extracted from the resonator through the output transducer. Two transducers are acoustically coupled to each other; therefore, in the OFF state, when the piezoelectricity is switched off in either of the BST thin films (by eliminating the DC bias voltage), there is no acoustic coupling between the input and the output ports. In this OFF state, the only path to the output is the stray capacitance between the top and bottom electrodes, which is desired to be zero. Due to the small stray capacitance, the off state isolation of the stacked crystal filter unit cell is expected to be high compared to the conventional ladder-type filters.

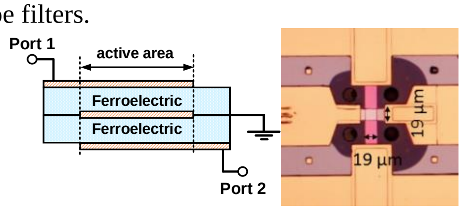

Fig. 3. (a) A single pole ferroelectric stacked crystal filter configuration, and (b) a micrograph of a fabricated device.

A BST SCF with a mode 2 resonance at 3.6 GHz is designed and fabricated for a system impedance of 50 Ohms. As shown in Fig. 3(b), a single pole BST SCF unit cell occupies a reduced space (<400 µm^2) as compared to the conventional ladder-type filter unit cell. The measured transmission response of a BST SCF in its ON and OFF state is plotted in Fig. 4. The BST SCF unit cell provides a higher out of band rejection and OFF state isolation as compared to single-stage the ladder-type counterpart, with a similar minimum IL and BW. However, as shown in Fig. 4, the BST SCF near-in rejection is not as sharp as the ladder-type filter. In order to improve the overall filter response, miniature intrinsically switchable hybrid filters can be designed by combining a ladder-type BST FBAR filter and a BST SCF. The near-in response of a BST SCF would improve with a ladder filter, increasing the near-in skirt selectivity while maintaining the high out of band rejection and OFF state isolation of the SCF.

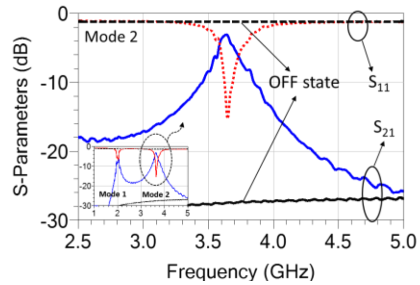

Fig. 4. Measured S-parameters of the intrinsically switchable single pole BST SCF unit cell. Inset shows the response of the filter over a wider range of frequency, which includes mode 1 and 2. In this work, the device is optimized for mode 2 operation.

IV. Conclusion

In this project, we have presented a novel mode switchable BAW resonator. The electromechanical coupling coefficient of the longitudinal thickness modes for a multi-layer ferroelectric resonator, presented herein, is calculated, demonstrating selective excitation of higher-order modes with constant K_{eff}^2 values. Mode-switchable resonators can simplify the RF frontend modules by eliminating the need for external switches and also reducing the overall number of required filters. The idea is experimentally validated through the fabrication and measurement of a bilayer BST resonator that selectively resonates at its first or second harmonic modes. Furthermore, An intrinsically switchable ferroelectric BST based stack crystal filter is designed and fabricated for the first time, which is the smallest acoustic wave filter in the literature. The results of this work are published in multiple journal articles [2], [4], [5], and conference proceedings[1], [3].

References

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