Reconfigurable Radios Employing Ferroelectrics

Milad Zolfagharloo Koohi and Amir Mortazawi part of our lives, continuously improving the qualityofour everyday activities. A multitude of functionalities are offered by recent generations of mobile phones, resulting in a significant adoption of wireless devices and a growth in data traffic, as reported by Ericsson [1] in Figure 1. To accommodate consumers' continuous demands for high data rates, the number of frequency bands allocated for communication by governments across the world has also steadily increased. Furthermore, new technologies, such as carrier aggregation and multiple-input/ multiple-output have been developed. Today's mobile devices are capable of support ing numerous wireless technologies (i.e., Wi-Fi, Bluetooth, GPS, 3G, 4G, and others), each having its own designated frequency bands of operation. Bandpass filters, multiplexers, and switchplexers in **RF** transceivers

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are essential for the coexistence of different wireless technologies and play a vital role in efficient spectrum usage. Current mobile devices contain many bandpass filters and switches to select the frequency band of interest, based on the desired mode of operation, as shown in Figure 2. This figure presents a schematic of a generic RF front end for a typical mobile device, where a separate module is allocated for the filters. Each generation of mobile devices demands a larger number of RF filters and switches, and, with the transition toward SG and its corresponding frequency bands, the larger number of required filters will only add to the challenges associated with cell-phone RF front-end design.

Currently, only acoustic (piezoelectric) filters can meet the stringent filter requirements in RF front ends [2]. Although they are capable of meeting the requirements for communication, acoustic filters also require external switches to select among different frequency bands of operation (Figure 2).

The addition of switches to the RF modules adds to their complexity and loss. In today's cell phones, more than 40 filters and switches are employed, and this number is expected to exceed 100[2], which poses significant challenges arising from the cost, size, and power constraintson RFfrontends.Apossible approach to address these challenges is to integrate both switching and filtering functionalities onto a single device by replacing the combination of switchplexers and conventional bulk acoustic wave (BAW) filters with intrinsically switchable acoustic filters. Figure 3 compares a simplified version of today's RF front-end block diagram [3] with the envisioned RF front end based on switchablefilters.

Thebuildingblocks of switchable filters are switchable acousticres on and off with an application of de bias voltage. Switchable resonators are realized through electrostatic (capacitive) [4]-[8] or electrostrictive [9]-[16] transduction mechanisms. The

performance of electrostatic-and electrostrictive-based switchable resonators is compared

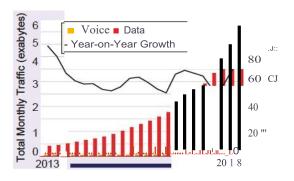


Figure 1. Data traffic has increased nearly 60% per year over the past few years (1).

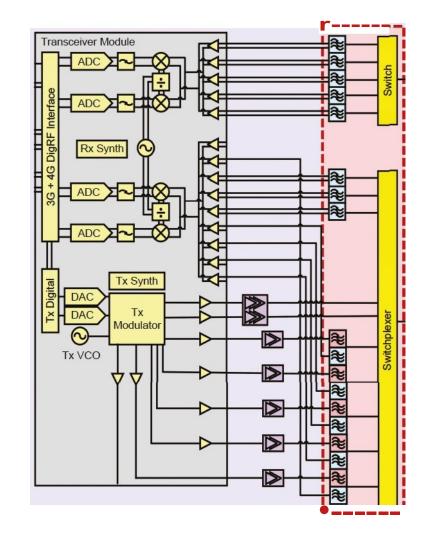


Figure 2. A generic RF front end for a mobile device. DigRF: digital RF; Tx: transmitter; ADC: analog-to-digital converter; Rx: receiver; DAC: digital-to-analogconverter; VCO: voltage-controlledoscillator; Synth: synthesizer.

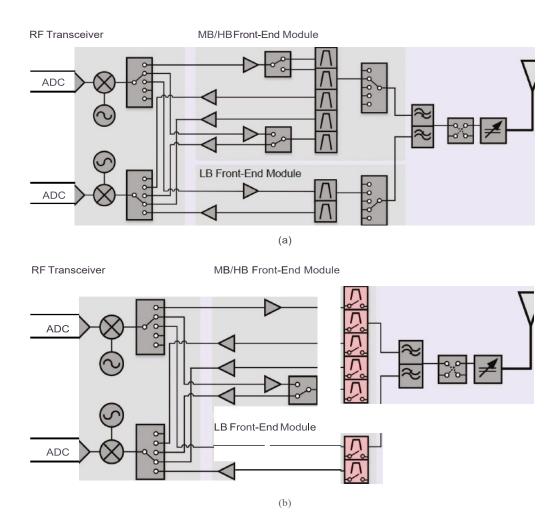


Figure 3. (a) A simplified block diagram for today's RF front-end architecture [3]. (b) The envisioned architecture based on switchable filters. LB: low band; MB: middle band; HB: high band.

TABLE 1. A comparison of switchable resonators based on transduction mechanisms [17].

Prope rtie s	Electrostatic Transduction- Based Resonat ors	Electrostrictive Transduction- Based Resonators	
Quality factor	Very high (>10,000)	-400"	
Electromechanical coupling	Low	High	
Motional resistance	Very high	Low	
Typical resonance frequency	Low (<2 GHz)	High	

[&]quot;Q and Kt a re reported for regular (noncomposite) BST thin-film BAW resonators.

in Table 1. High quality (Q) factors on the magnitude of 10,000 are achievable in electrostatically transduced resonators. However, such resonators possess large motional resistances, limiting their use in RF systems with 50-Q standard impedance due to significant impedance mismatch. Also, the low electromechanical coupling coefficient (KI) of these resonators limits the maximum achievable bandwidth (BW) of the filters that employ such resonators. On the other hand, switchable resonators based on electrostrictive transduction exhibit high Kt and low motional resistance and are preferred for RF systems. In these resonators, ferroelectrics barium strontium titanate [Bax Sr{l-x}Ti0 3 (BST)] is used for electromechanical transduction.

Multifu nctional ferroelectric BST exhibits several desirable characteristics that can be employed for the design of intrinsically switchable resonators. These characteristics include a large electrostriction coefficient, high relative permittivity, low loss tangent, and compatibility with integration onto a silicon (Si) su bst rate. This article highlights the importance of ferroelectric BST and describes recent progress in the area of voltage-controlled BST devices.

Ferroelectric BST

Ferroelectric BST is a multifunctional material that exhibits distinctive characteristics, depending on its operating temperature with respect to its Curie temperature (Tc), as seen in Figure 4(a) [18], [19]. Below the Tc, the BST material is in the ferroelectric phase and exhibits a hysteresis loop for polarization, making it suitable for memory applications, such as nonvolatile memories [18]-[20]. However, above Tc, the BST material operates in the paraelectric phase and possesses multiple characteristics suitable for RF/microwave device applications. For instance, BSTs high permittivity (e, >100) and electric-field-dependent properties, as shown in Figure 4(b), have been applied in high-k capacitors and varactors [18]-[22]. Of special interest is the BSTs electric-field-induced piezoelectric effect,

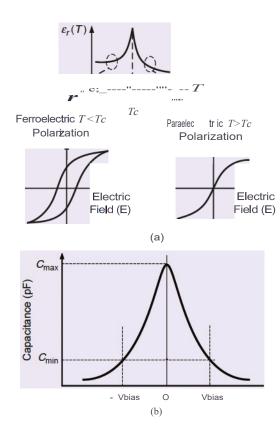


Figure 4. The temperature-dependent response of ferroelectric BST in its ferroelectric (below Tc) and paraelectric phase (above TJ. (b) A typical BST varactor in paraelectric phase provides a bell-shaperesponse as a function of voltage.

Currently, only acoustic (piezoelectric) filters can meet the stringent filter requirements in RF front ends.

known as *electrostriction*, which enables BST acoustic resonators to be intrinsically switchable.

BST has a cubic perovskite unit-cell structure in its paraelectric phase, as shown in Figure 5. Thus, the components of the piezoelectric tensor are all zero in this phase, due to its centrosymmetric structure. However, when a de bias voltage is applied across the ferroe lectric materia l, the electric field displaces the center titanium ion in the BSTs tru ctu re, leading to a nonsymmetric structu re that exhibits a piezo- electric effect (i.e., field-induced piezoelectricity). In conventional piezoelectric materials, the relationship between the electric and acoustic fields is approximately linear in the small signal domain, as shown in Figure 6(a); however, in ferroelectrics, with a centrosymmetric paraelectric phase, the induced strain and electrical polarization are related by electrostriction (1) [23]. The electric polarization under an applied electric field E can be expressed by (2):

$$u = QP^2 \tag{1}$$

$$P = P_S + xE, \tag{2}$$

where u is strain, Q is the electrostriction coefficient,

and X is the susce p tibility of the ma terial. Substituting (2) in (1) results in the following [23]:

$$U = QP + (2QP, x + Qx^{2}E)E.$$
 (3)

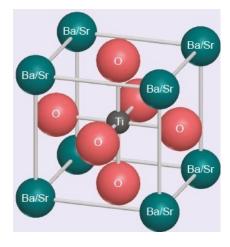


Figure 5. The crystalline structure of perovskite ferroelectric BST in the paraelectric phase undera zerodebias voltage (adapted from[521). This exhibits no piezoelectric characteristic due toa centrosymmetric unit cell. Ba:barium; Sr:strontium; Ti: titanium; 0: oxygen.

High-performance, compact, and low-cost BAW resonators are essential components of modern wireless communication systems.

The two terms inside the parentheses of (3) make up the effective piezoelectric coefficient of the material. While the first term of the effective piezoelectric coefficient is constant, the second term is E-field dependent. Therefore, electrostriction can be considered as E-field-induced piezoelectricity. In the paraelectric phase, where spontaneous polarization is zero (Ps=0), the electromechanical transduction occurs primarily through the electric field or by a voltage-induced piezoelectric effect that originates from BST's strong electrostriction, as shown in Figure 6(b). This unique property can be used to control the mechanical/electrical coupling in BST with a de biasvoltage, and it has been employed in designing intrinsically switchable BAW devices.

Intrinsically Switchable AW Resonators

High-performance, compact, and low-cost BAW resonators are essential components of modern wireless

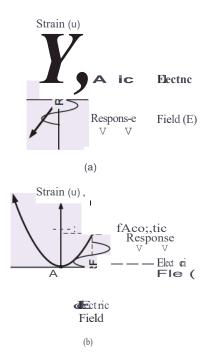


Figure 6. (a) Theinteractions of acoustic electric fields in typical piewelectric material. (b) The electric field-induced piezoelectricity of BST as a result of its strong electrostriction property. Under a zero deelectric field (E=0 Vim, point A), the slope of the curve is zero, and no AW is excited; biasing the material under a de electric field (point B) enables the material to couple the electric energy into AWs.

communication systems. BAW resonators consist of a piezoelectric transduction layer sandwiched between two metal electrodes. RF signals applied to the electrodesexcite AWs that propagate within thebulk of the device. The propagating BAWs will, in turn, generate an electrical response. The AWs are confined within the resonator due to the acoustic impedance mismatch between the resonator body and its surrounding environment. There are two primary methods of confining the BAWs, and BAW resonators are classified into two different categories based on which method is used. The first type of BAW resonator is the solidly mounted resonator (SMR), which uses an acoustic Bragg reflector, comprising alternating quarter-wavelengths of high- and low-acoustic impedance materials, to confine the acoustic energy within a particular set of frequencies. The second type is the thin-film BAW resonator (FBAR). This is made using micromachining techniques to remove the material surrounding the resonator body. The FBAR relies on the large acoustic impedance mismatch between the resonator body and the surrounding air/vacuum to confine BAWs. Both FBARs and SMRs have resonance frequencies determined by the thickness of the thin films that make up the device. Furthermore, both types of BAW resonatorshave been used heavily in the telecommunications industry, each with its distinct advantages. Simplified cross-sectional views of SMRs and FBARs are shown in Figure Z

BAW resonators (FBARs and SMRs) based on ferroelectric BST possess several unique features that can

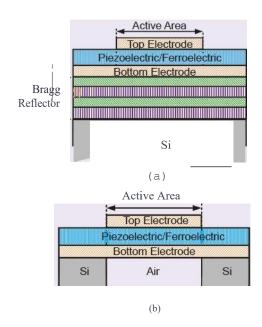


Figure 7. Cross-sectionalviews of typical (a) SMRs and (b) FBARs.

simplify RF front ends for future mobile devices. Due to BST's strong electrostriction properties, BST resonators can be switched on and off with the application of de bias voltage [9]-[17], [24]-[28]. Furthermore, BST has a high relative permittivity, which allows for the design of much smaller resonators compared to those based on traditional piezoelectric material, significantly reducing the size of RFfront-end modules. Figure 8 shows a photograph of a fabricated intrinsically switchable BSTFBAR and the measured S11 plotted on a Smith chart in its on and off states. As shown in the figure, the device in its off state behaves like a simple capacitor. Applying de bias voltage across the resonator electrodes transfers the device to its on state. The *Kt* of 8.6% with a mechanical *Q* factor (Om) of 360 is

achieved for a BST FBAR by Zolfagharloo Koohi et al. [26]. Switchable BST-based SMRs with Kt and Qm of 2.5% and 350, respectively, are also demonstrated by Vorobiev et al. [14].

Furthermore, additional low-loss materials, such as Si or Si dioxide (Si0 2), can be added to the BST resonator structure (composite BST FBAR) for enhancing certain performance aspects of the device, as depicted in Figure 9(a). By following the method based on the ID acoustic transmission line model described by Sis [17] and carefully determining composite FBAR design parameters including the BST-to-Si/Si02 thickness ratio, resonance frequency, and mode number, the desired resonator characteristics (i.e., *Q*, *Kt*, and thermal coefficient of frequency) can be achieved [17]. A

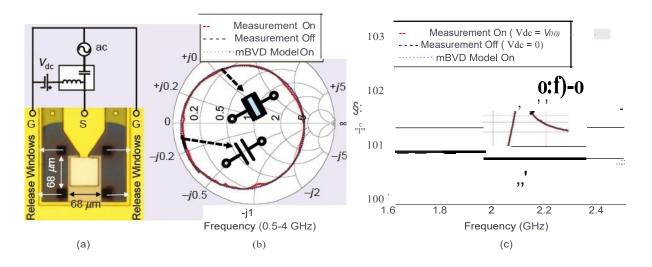


Figure 8. (a) A fabricated BST FBA R. (b) The reflection coefficient on a Smith chart. (c) The magnitude of input impedance for the measured one-port switchable BST FBAR in its on $(Vdc = 70 \ V)$ and off states $(Vd, = 0 \ V)$ [24). mBVD: modified Butterworth- Van Dyke; G: ground; S: signal.

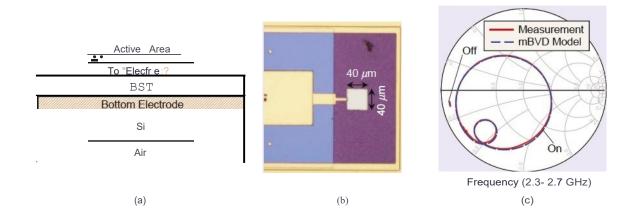


Figure 9. (a) A cross-sectional view and (b) a photograph of a fabricated one-port BST-on-Si FBAR. (c) The measured reflection coefficient plotted on a Smith chart in its on $(Vdc = 60 \ V)$ and off $(0 \ V)$ states [24].

composite BST-on-Si FBAR with a *Qm* factor of 970 is reported by Lee and Mortazawi [24]. A photograph of the device and the measured S11 in its on and offstates are provided in Figure 9(b) and (c).

Switched-mode BAW resonators have been introduced to design reconfigurable multiband RF filters

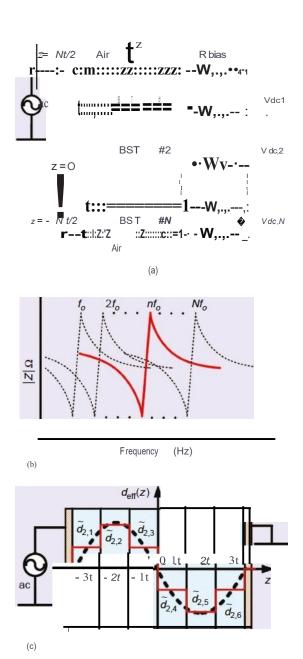


Figure 10. The multilayer ferroelectric resonator: (a) structure and (b) the magnitude of the impedance for different states of the device.(c) An example of the ideal nonuniform pattern of effective piezoelectric coefficient for selective excitation of only mode 2 in a six-layer ferroelectric BAWresonator (dashed line). The stepwise solid line is the actual realization of such a pattern. The piezoelectric coefficient in the last three layers is negative. Piezoelectricityin each BST layer is a function of the magnitude and polarity of the applied debias voltage [33].

[29] - [31], [33] . Such resonators are constructed by depositing multiple layers of ferroelectric BST sandwiched between thin-film electrodes.

Switched-mode resonators selectively operate at various resonant modes, as shown in Figure 10(a) and (b), without affecting the electromechanical coupling coefficient. This is accomplished by exploiting the electric-field-induced piezoelectricity and negative piezoelectricity in multilayer BST [33]. 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 de bias voltages [e.g., Figure 10(c) represents the required pat-

tern 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.

A dua 1-resona nce, switched-mode ferroelectric FBAR is experimentally demonstrated by Zolfagharloo Koohi and Mortazawi [31], where the resonator is constructed by employing two BST layers sandwiched between electrodes, as shown in Figure 11(a). The device can selectively resonate at its fundamental mode in the 2-GHz band (mode 1) or its second eigenmode in the 3.6-GHz band (mode 2). The de bias voltage configuration for each mode is shown in Figure II(a). A cross-sectional view of the fabricated deviceand its impedance response are provided in Figure ll(b) and (c), respectively. When either of the modes is selected by applying the corresponding set of de bias voltages, the other mode is fully suppressed, as shown in Figure 11. The device is switched off when the de bias is removed.

Another type of acoustic resonator is the contour (lateral)-mode resonator, which has a resonance frequency dictated by both the lateral dimensions of the transduction layer and the geometry of its bottom and top electrodes. Contour-mode resonators are usefulsince their resonance frequency can be determined through the lithographical process. Hence, a large number of resonators with varying resonance frequencies can be realized all across the same wafer without increasing the number of processing steps.

Ferroelectric barium titanate (BTO) is used in the design of contour-mode resonators due to its nonzero effective d 31 piezoelectric coefficient when polarized by an external electric field. This property allows the excitation of laterally propagating AWs within the acoustically resonant cavity (in its on state) with the application of an RF signal applied across the electrodes. Having a Tc of near 110 °C, BTO is in its ferroelectric phase at room temperature and possesses a spontaneous polarization along with the electrostriction effect. Therefore, BTO resonators exhibit a weak resonance even in the absence of a de biasvoltage. Zero

bias resonance can be turned off by reducing the polarization in BTO thin film with an application of a small de bias voltage (-1 V) across the electrodes. Further increasing the de bias voltage leads to polarization in the direction opposite to the original polarization and a strong piezoelectric response due to BTO's large electrostriction coefficient [28].

An example of a lateral-mode device is the interdigitated contour-mode resonator, which consists of a rectangular BTO thin film with interdigitated top and/or bottom electrodes. Interdigitated contour-mode resonators can be designed as either thickness-field-excitation (TFE) or lateral-field-excitation (LFE) devices. In TFE resonators, the electric field vectors are approximately perpendicular to the plane of the thin film. In LFE resonators, the electric field vectors have a component

parallel to the plane of the thin film. An example of a TFE interdigitated contour-mode resonator that excites under the application of an RF signal and de bias to the interdigitated electrodes is shown in Figure 12[28].

The resonance frequency of the contour-mode resonator, shown in Figure 12, is determined by the width

and spacing of the interdigitated electrodes as well as the material properties of the resonator body. A photographofa fabricated intrinsically switchable interdigi-

tated lateral-mode resonator as well as its impedance response in on and off states is shown in Figure 13. These resonators can be used as building blocks for monolithic, multifrequencyswitchable RF circuits.

The electrical behavior of ferroelectric resonators in the on state can be represented by a modified Butterworth-Van Dyke model, shown in Figure 14(a.) In this figure, the motional branch is modeled by a capacitor (Cm) in series with an inductor (Lm), forming the series

resonator. The additional resistor (Rm) represents the mechanical loss factor. The electrical branch consists of a static capacitance (C,) along with resistance R,, which represents the dielectric loss. Under zero de bias voltage, the resonator is in its off state, and the motional branch in this model (*Lm*, *Cm*, Rm) vanishes, as shown in Figure 14(b). These lumped-element circuit models

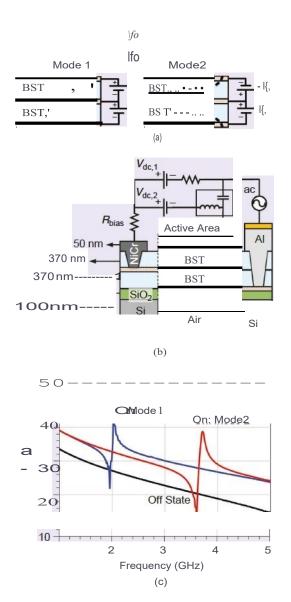
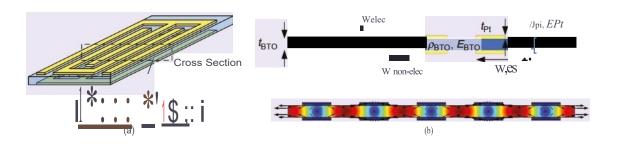


Figure 11.(a) The simplified structure of adual-band, switched-modeferroelectric FBAR inmodes 1 and 2 with their corresponding debias voltage and the standing wavestrain field distribution. (b) A cross-sectional view of the fabricated devices and the measurements setup as well as (c) the measured impedance response of the resonator in each mode along with its off-state response. NiCr: nickel chromium.



 $\textbf{Figure 12.} \ (a) \ A\ TFE\ contour-mode\ interdigitated\ resonator\ and\ (b)\ the\ corresponding\ strain\ fields\ in\ the\ resonato'rs\ on\ state}$ Authorized licenseduse limited to: University of Michigan Library. Downloaded on December 28,2020\ at 00:23:48\ UTC\ from\ IEEE\ Xplore\ Restlictions apply.

IEEE maowave magazine 121

May 2020

are used to design intrinsically switchable ferroelectric filters and predict their responses in on and off states.

Comparison of BST Resonators With State-ofthe-Art Piezoelectric Resonators

A co m pa r ison between the electrical and acoustic parameters of the latestreported BAW BST resonators and state-of-the-art aluminum-nitride (AIN) FBARs as well as zinc-oxide (ZnO) SMRs is provided in Table 2. As shown in the table, these devices provide, in addition to the intrinsically switchable behavior of BST

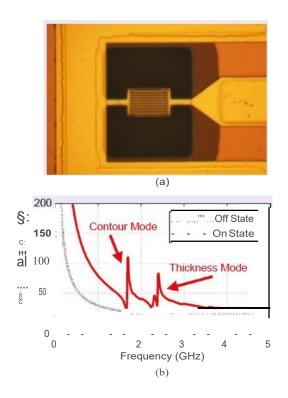


Figure 13. (a) A fabricated BTO-based TFE contour-mode interdigitated resonatorand (b) its impedance response in theonand off state [28].

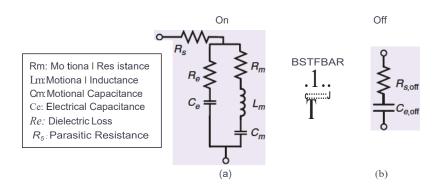


Figure 14. (a) An on-state lumped-element mBVD model for a one-port switchable BST FBAR and (b) its off-state capacitive model.

FBARs, an effective KV of 8.6%, which is larger than the standard values reported for AlN and ZnO resonators. There have been efforts to increase the Kl of AlN resonators by doping AlNwith different materials [e.g., scand ium-AlN, magnesium-AlN, (magnesium, zirconium)-AlN]. However, adding a dopant to AlN significantly reduces the Q factor of the resonators [3], [32]. A larger Kl of BST allows the design of filters with a widerBW.

Another important parameter is the relative dielectric constant (permittivity) of the piezoelectric / ferroelectric materials, which correlates to the form factor of the devices. The permittivity of BST (er,BST=120) is significantly larger than that of AIN (er AIN = 8.3) by a factor greater than 10 and leads to miniaturized BST-based resonators and filters.

The acoustic velocity of BST is also comparable with that of AIN, allowin g the design of switchable BST FBARs at relatively high frequencies. However, the Q factor of reported BST resonators remains lower than that of state-of-the-art AIN FBARs, but it is expected that BST resona tors can achieve higher Q-factor values [51] through optimization of BST ferroelectric deposition conditions for better crystallinity and lower loss. To achieve a high Q factor, BST FBAR design features also need to be improved in terms of resonator shape, lateral boundaries, and optimization of acoustic dispersion [3]. On the other hand, BST's large KV can be traded off for a higher Q factor by designing composite resonators and adding a low-loss material (e.g., Si, S0 2, and others) to the resonator structure, as shown

in Sis[17].

Intrinsically Switchable Filters

Ferroelectric resonators are the building blocks for intrinsically switchable filters [36]-[41]. The two main categories of BAW filters are traditional electrically coupled ladder or lattice network filters and acoustically coupled filters. For example, a ladder-type filter, shown

in Figure 1S(a), consists of cascaded series-shunt-connected FBAR stages. To achieve a typical bandpassfilter response in this configuration, the resonance frequency of the shunt FBARs is shifted down, as shown in Figure 1 S(b). In the on state, when all BST resonatorsare turned onusingdebias voltages, the device represents a bandpass filter response; in the off state, under zero de bias voltage, it provides an isolation between the input and output ports, as shown in Figure IS(c). To desig n and simulate the behavior of switchable ladder-type BST FBAR filters, lumped-element models for BSTFBARs in the on and off state, provided in Figure 14, are used. The filters are designed following the image parameter method described by Lee and Mortazawi [38]. Based on this approach, the electrical capacitances of the series (C.,se) and shunt (Ce.sh) BST FB ARs in the on state can be determined

TABLE 2. A comparison of different FBAR technologies

Device	<i>f</i> , {GHz)	Q Factor	<i>K1</i> {%)	Acoustic Velocity (m/ s)	Switch-Ability	Reference
	, ,		. ,	,	•	
AIN FBAR	0.9	0, = 2,500	6.5	11,050	No	[51]
AIN FBAR Avago VII	2	0 = 4,000			No	(32], [34]
ZnO SMR	0.9	$O_{2} = 510$	6.6	6,350	No	(35], [51]
BST SMR (BadsSro1sTiO,)	5.2	Om = 350	2.5	5,600	Yes	[14]
BST-on-SiFBAR (Bao.sSro.sTiO,)	2.5	Om = 971	0.8	5,600 for BST	Yes	[24]
BST FBAR (BaosSro.sTiO,)	2	Om = 360	8.6	5,600	Yes	[26]

 $Q_{::}$ Q factor at the resonance frequency(indudes conductor loss and ac oustic loss). Q: Not specified

Qm: De-embedded Q factor at the resonance frequency (includes acoustic loss).

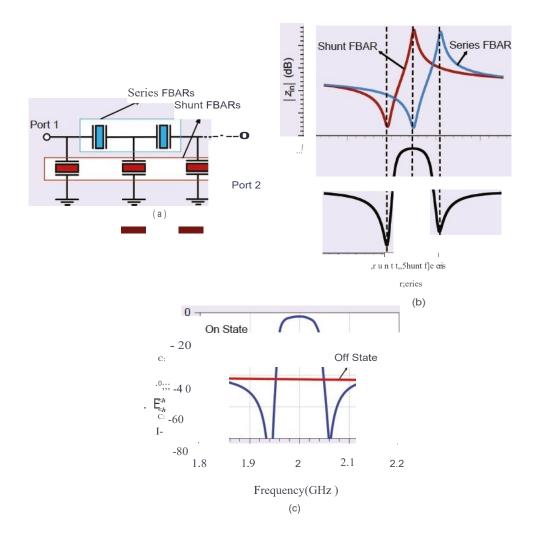


Figure 15. (a) A typical ladder-ty pe BAW filter schematic, (b) its principle of operation, and (c) the transmission response of an intrinsically switchable ladder-ty pe ferroelectric filter in its on and off states.

Acoustically coupled filters can provide high out-of-band rejection while also maintaining a small footprint.

using (4) and (5), given the filter specification, including fractional BW (FBW), system impedance {Zo}, and filter center frequency (me). Next, the structure of the BST resonators can be designed based on the 1D transmission line model discussed in Sis [17] to meet the required filter constraints:

$$C_{,,,,} = \left(\underbrace{\frac{1}{mcZov M}}_{\text{mcZov M}} \underbrace{\stackrel{M}{\longrightarrow} \frac{1 \text{ J}}{(1 + \text{v1} + FBW^2)}}_{FBW^2M} - 2,\right)$$
(4)

$$, c_{5} = \left(\frac{1}{2mcZo} \frac{M}{M} \times \frac{M}{M} - \frac{f(1+\sqrt{1+FBW^{2}}) - 2}{M} - \frac{1}{2mcZo} \right)$$
(5)

whereM is

$$M = (1+/1-1) fr$$

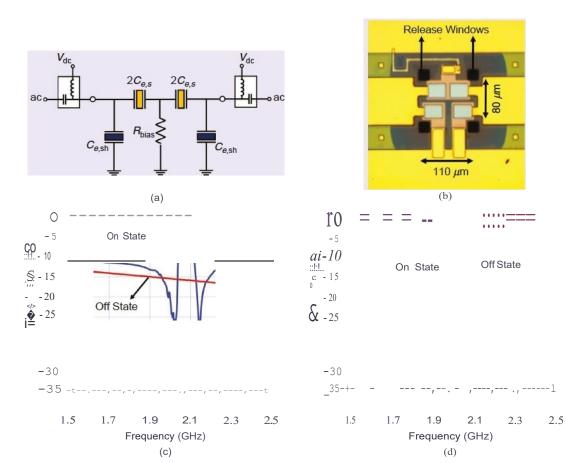
A schematic of a 1.5-stage n-network ladder-type intrinsically switchable BAW filter unit cell based on BST FBARs and a photograph of a fabricated filter are shown in Figure 16(a) and (b),respectively (39].

In thisfilter, the series FBAR is replaced by two doubled-sized FBARs to simplify the de biasing network, while Rbtas models the high-resistivity biasing line for the resonators. DC bias voltages are applied through bias tees connected to each port of the device. The measured transmission and reflection responses in the filter's on and off states are provided in Figure 16(c) and (d). In the on state, the filter provides a mini- mum insertion loss (IL) and FBW of 2.25 dB and 2.8% {58 MHz at 2.08 GHz}, respectively. Off-state isolation between the input and output ports exceeds 14 dB. The size of the filter active area occupies only 80 x 110 μm , which is notably smaller than conventional piezoelec-

Several filter unit cells can be cascaded in series to design higher-order filters with higher out-of-band rejection and isolation levels at the cost of a largerIL. Forexample, a 2.5-stage ladder-type BSTFBAR filter is

tric filters.

implemented in Zolfagharloo Koohi et al. [41]. A photograph of the filter as well as the transmission and reflection responses in its on and off states is shown



130 IEEEmcrONaVe magazine

May 2020

in Figure 17. The filter provides more than 25-dB outof-band rejection level and isolation between the input and output ports in the on and off state, respectively.

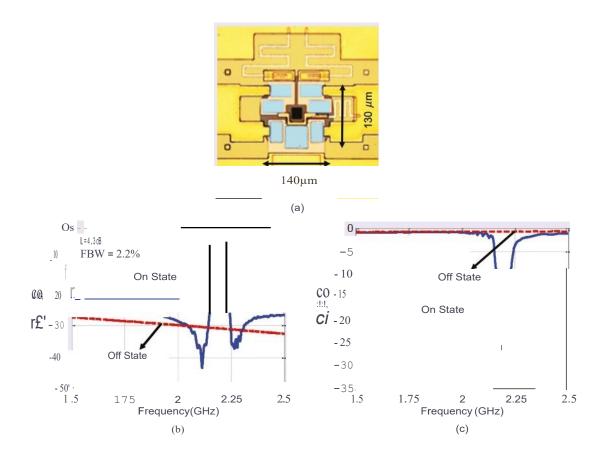
The increasing number of carrier aggregation band combinations demands a higher degree of linear-ity. To study the linearity of BST filters, a nonlinear model has been developed for BST resonators in Lee [42]. This model can be employed to optimize the BST filter structure and design highly linear switchable filters. When BST FBARs are biased beyond a certain voltage value (VoN), their properties, such as C, Qm, and Kl, are no longer a strong function of voltage [43), and the device is more linear. The third-order intercept point (IP:i) is a figure of merit used for weakly nonlinear devices associated with third-order intermodulation distortion. The BST FBAR filter IP3 in its

on state (Vbias > Von) is investigated by transmitting two tones of the same power (N=10 MHz) within the filter passband and recording the output signal power level, as shown in Figure 18(a). The measured input IP3(1IP:J) for the filter is 47 dBm [41), which is shown in Figure 18(b). To further enhance linearity, a cascaded structure, where each resonator is replaced with multiple larger series-connected resonators having an overall capacitance equal to the original resonator [51),

Switched-mode resonators selectively operate at various resonant modes without affecting the electromechanical coupling coefficient.

was demonstrated for BSTresonators by Zolfagharloo Koohi and Mortazawi [43].

The second category of BAW filters includes acoustically coupled filters, in which the resonators are coupled either vertically or laterally, depending on the resonator structure. Acoustically coupled filters can provide high out-of-band rejection while also maintaining a small footprint. Intrinsically switchable acoustically coupled ferroelectric filters can even reduce the size further by eliminating the need for external switches. In vertically coupled filters, the resonators are stacked on top of each other such that the acoustic coupling is perpendicular to resonator surfaces. Stacked crystal filters (SCFs) and coupled resonator filters are well-known examples of vertically coupled acoustic filters [51). An intrinsically switchable BST SCF was recently demonstrated by Zolfagharloo Koohi et al. [44), where



 $\textbf{Figure 17.} (a) A \ 2.5 - stage \ BSTFBAR filter. (b) The transmission \ and \ (c) reflection \ responses \ of the filter in its on and \ off states \ [41].$

the size of the filter unit cell was only $19 \times 19 \mu m$. In laterally coupled acoustic filters, the resonators are fabricated on the same plane, separated by a gap between the electrodes. In such filters, the acoustic coupling takes place in a lateral direction parallel to the resonator surfaces. Monolithic CFs (MCFs), among the first BAW filters to employ lateral coupling, have been used since the 1960s for various applications, such as intermediate frequency filters in radios. Quartz crystals have been the material of choice in traditional MCFs.

Recently, laterally coupled acoustic filters have been implemented using thin-film piezoelectric materials (AlN and ZnO). Due to their significantly diminished thicknesses, thin-film laterally coupled acoustic filters operate at much higher frequencies compared to MCFs, making them suitable for RF and microwave applications. An intrinsically switchable BTO-based laterally coupled filter was designed and fabricated, as shown in Figure 19(a) [37]. The measured S-parameters of the filter are provided in Figure 19(b) and (c). As

shown in the figure, the filter can provide more than 40-dB out-of-band rejection in the on state and isolation between the input and the output ports in the off state.

Power Supply Signal Generator fc+M/2Spectrum Analyzer 0 0 Bias Tee **GSG** Bias-Tee Isolator **Probes** Power OUT Combiner (a) 50 $OIP_3 = 42.7 \, dBm$ е ID 0 <ii a., Fundamental - 50 IM₃ cı Measurement - 100 40 0 10 20 30 50 Available Input Power (dBm) (b)

Figure 18. (a) A two-tone measurement setup for intermodulation distortion of the 2.5-stage BST FBAR filter and (b) its measured IP3 data [41]. DUT: device under test; GSG: ground-signal-ground.

Intrinsically Switchable Filter Banks

In trinsically switchable BST filters of different frequencies are connected in parallel to form intrinsically switchable multiband filter banks. The

ultimate goal of ferroelectric filter banks is to eliminate the switches dedicated to selecting the frequency bands from the RF module. A possible way of realizing intrinsically switchable ferroelectric filter banks is experimentally demonstrated by Zolfagharloo Koohi and Mortazawi [45], [46]. A tripleband intrinsically switchable

filter bank is designed and fabricated, where each filtering path consists of a 2.5-stage

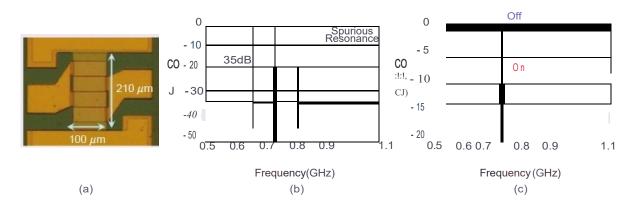


Figure 19. (a) A fabricated intrinsically switchable acoustically coupled BTO filter. The (b) transmission and (c) reflection response of the filter in its onand off states. (Adapted from [37].)

ladder-type BST filter placed between series BST metal-insulator- metal varactors, as shown in Figure 20. The purpose of using BST varactors here is to improve the isolation of the filter without significantly impacting IL or adding to fabrication complexity.

The intrinsically switchable filter bank operates as follows. When a filter path is switched on, its constituent resonators are turned on, and the varactors are tuned to their highest capacitance such that they are at their lowest impedance, **which** occurs when the voltage across their terminals is set to 0 V. When the filter is switched off, the constituting resonators are turned off, and the varactors are set to their lowest capacitance such that they present a high impedance, which occurs when the voltage across their terminals is high.

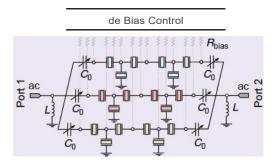
In this example, the BST varactors are fabricated on the same Si wafer along with the BSTFBARs using a similar fabrication process; therefore, the filter bank structure and the fabrication process are simplified, and the overall footprint of the filter bank is reduced, compared to traditional piezoelectric filter banks where external switches are employed. The series varactors in Figure 20 are either under zero bias or large bias voltage and are not used in their voltage-sensitive region. Therefore, the addition of BST varac-

tors to the filter structure in this example does not

contribute significantly to the nonlinearity of the filter. To further reduce the effect of varactors on linearity, BST varactor linearization techniques presented by Fu et al. [47] can also be employed. The basic concept described in Fu et al. [47] is to reduce the RF swing across the ferroelectr ic varactors by connecting multiple capacitors in series.

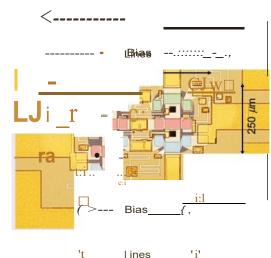
A photog raph of the fabricated triple-band BST FBAR filter is shown in Figure 21(a, and its measure-

ment results are depicted in Figure 21(b.)In this case, with all filters switched off, the signal transmission is lower than - 27dBover the frequency range of 1.5-2.5 GHz (off-state transmission is shown by a dashed line). Turning on each of the three individual filters



provides bandpass responses with center frequencies of 1.85, 1.96, and 2.04 GHz, respectively. The size of the active area for this filter bank is only $250 \times 480 \ \mu m$, which is significantly reduced compared to previously reported switchable acoustic filter banks based on piezoelectric materials [46]. The larger IL of the measured filter bank, compared to the standalone filter of Figure 17, is mostly attributed to the varactors' losses, due to the fact that the BST depos ition conditions in this article are not optimized for varactor fabrication.

The intrinsically switchable ferroe lectric filter bank example presented here demonstrates the feasibility of fabricating BST-based switchable filter banks. However, optimized BST filter banks are yet to be designed to meet state-of-the-art RF front-end specifications. Future work involves the enhancement of BST FBARs' figure of merit $(Qm \times K)$ as well as the development of a design methodology for the switchable filter banks. Improving BST FBARs' parameters (Qm and K?) is essential for designing low-loss switchable filters and is part of the ongoing research efforts following the methods described previously. The simulation results



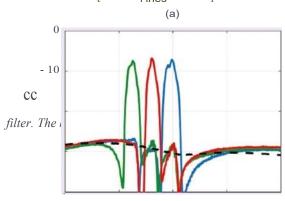
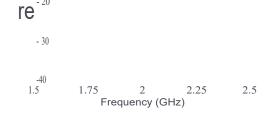


Figure 20. The designed multiband 2.5-stage BST FBAR



May 2020

Figure 21. (a) The fabricated triple-bandBST FBAR filter and (b) its measured transmission response. The measured off-state (when all of the filters are turned off) response is also provided in adashed line. (Adapted from [46].)

(b)

IEEE maowave magazine 133

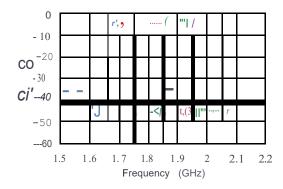


Figure 22. The simulation results for a switchable filter bank consisting of four 2.5-stagefilters in their on state, superimposed in one figure.

of a switchable filter bank using a circuit topology similar to Figure 20 based on BST FBARs with a K and Om of 8% and 800, respectively, are shown in Figure 22. In this simulation, a modest capacitance tunability of 4:1 for BST varactors (Qvar = 100) and a shunt inductance of 3.5 nH (Qind = 50) are assu med. Based on these parameters, the intrinsically switchable filter bank provides a minimum IL of 2 dB, out-of-band rejection and isolation levels of more than 40 dB, and an FBW of 3% at center frequencies of 1.7, 1.8, 1.9, and 2 GHz. The performance of the filterbank can be further enhanced by optimizing the filter-bank configuration for minimizing the reactive loading effect of the offstate filters without using varactors. A possible way is to employ the approaches developed for the synthesis of multiplexers with the manifold configuration as described in Bonastre [48] and Fattinger et al. [49].

Summary and Conclusions

Sales of RF front ends are expected to reach US\$18 billionby 2020, and the growing number of required RFfilters is the main driver for this businessopportunity [50]. For multiband operation, RF filters are currently used in conjunction with switchplexers to select the desired bands and mode of operation. The switches within RF modules can be eliminated by employing reconfigurable filters to considerably reduce the size, complexity, and cost of future RFfront ends. This article reviewed recent progress on reconfigurable RF acoustic devices based on thin-film ferroelectric BST. Ferroelectric BST possesses several unique characteristics, including electric-field-induced piezoelectricity, field-dependent permittivity, and high relative permittivity, that are employed in the design of reconfigurable RF devices. The BST devices discussed here demonstrate the feasibility of fabricating intrinsically switchable resonators, filters, and filter banks aimed at simplifying future RF frontends by eliminating the need for external switches.

Future work includes further optimization of thin-film BST composition and deposition conditions for designing resonators with an improved *Qm* and *Kr*. Fur thermore, a systematic design process must be developed for low-loss, multiban d filters and filter banks.

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