Nonlinear Performance of BAW Filters Including BST Capacitors

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Abstract. *This paper evaluates the nonlinear effects occurring in a bulk acoustic wave (BAW) filter which includes barium strontium titanate (BST) capacitors to cancel the electrostatic capacitance of the BAW resonators. To do that we consider the nonlinear effects on the BAW resonators by use of a nonlinear Mason model. This model accounts for the distributed nonlinearities inherent in the materials forming the resonator. The whole filter is then implemented by properly connecting the resonators in a balanced configuration. Additional BST capacitors are included in the filter topology. The nonlinear behavior of the BST capacitors is also accounted in the overall nonlinear assessment. The whole circuit is then used to evaluate its nonlinear behavior. It is found that the nonlinear contribution arising from the ferroelectric nature of the BST capacitors makes it impractical to fulfill the linearity requirements of commercial filters.*

Keywords

BAW filter, resonator, nonlinear, ferroelectric, BST.

1. Introduction

BAW technology has suffered tremendous improvements since its invention that have made it possible to be now a technology that is widespread in wireless devices [1]. Still, increasingly stringent communication standards and a very high market competition push for even higher demands of performance that require improvements at all levels. One key aspect of BAW technology is the fact that each resonator shows two resonances, thus limiting the circuit topology to implement filters [2]-[4]. Although more advanced options in BAW exist, like Coupled Resonators Filters (CRF), they still have not reached commercial status due to poor fabrication yield. Therefore, current topologies are limited to ladder and lattice, the first being single ended and the second one balanced and both requiring two sets of resonators at different frequencies to implement the pass-band [3].

A variation of the lattice topology involves replacing the cross BAW resonators for capacitors having the same capacitance as the series resonators, so that the bandwidth would be considerably shrunk but the electrostatic capacitance still cancelled. An advantage of this solution is that now one can choose any dielectric material for the capacitor to miniaturize it. To this regard, this work presents simulations on a BAW filter of this type, where the dielectric of choice for the crossed capacitors is BST, showing $\varepsilon_r = 320$ and thus a high degree of miniaturization. More specifically, we discuss on the nonlinear performance of such a solution, given that BST is a well-known material for its high degree of tunability [5].

2. BAW Filter

The filter that is being discussed on this work is implemented with BAW resonators and BST capacitors, on a balanced configuration showing two lattice sections to have a central frequency of 2.155 GHz. Next, we discuss on each of these technologies and their corresponding nonlinearities, along with their final implementation in the filter.

2.1 Single BAW Resonator

The BAW resonator used for this work is of a Solidly Mounted Resonator (SMR) type [2] with layer materials and thicknesses as shown in Tab. 1.

SiN	200 nm
Mo	250 nm
AlN	1000 nm
Mo	250 nm
SiO2	1000 nm
W	500 nm
SiO2	500 nm
W	800 nm
SiO2	500 nm
Si	725 µm

Tab. 1. BAW resonator layers, top to bottom.

Its modeling is accomplished by use of the Mason circuit model [6], so that the stress and strain fields are taken into account for all layers of the stack; this also enables its nonlinear simulation. The Mason model is appropriate because the acoustic fields are referenced to ground on it, thus providing a better understanding when extending it to the nonlinear domain.

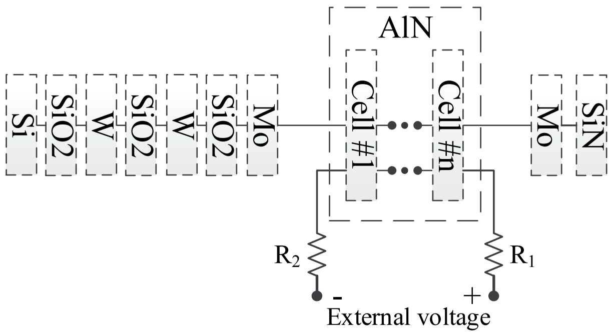

Fig. 1. BAW resonator circuit model implementation, following the Mason model approach. Electro-acoustic coupling occurs in the piezoelectric layer, whereas acoustic propagation occurs along the entire materials stack.

2.1.1 Nonlinear Modeling

A complete model for a BAW resonator extended to the nonlinear domain is found in reference [7]. Its derivation is based on the internal energy and its corresponding thermo-dynamical relations up to third-order, which along with measurements, allow for the identification of the dominant nonlinear terms. The constitutive equations for piezoelectricity are

$$T = c^E S - eE + \Delta T_{NL}\,, \tag{1}$$

$$D = eS + \varepsilon^S E + \Delta D_{NL} \tag{2}$$

with T, S, E and D being the stress, strain, electric field and displacement field respectively and c^E, e and ε^S the elasticity, piezoelectric coefficient and permittivity. The nonlinear terms ΔT_{NL} and ΔD_{NL} are:

$$\begin{aligned}\Delta T_{NL} &= \frac{1}{2}\left(c_2^E S^2 - \varphi_3 E^2\right) + \varphi_5 SE \\ &+ \frac{1}{6}\left(c_3^E S^3 - e_{3,E} E^3\right) + \frac{1}{2}\left(\chi_7 SE^2 - \chi_9 S^2 E\right),\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta D_{NL} &= \frac{1}{2}\left(\varepsilon_2^S E^2 - \varphi_5 S^2\right) + \varphi_3 SE \\ &+ \frac{1}{6}\left(\varepsilon_3^S E^3 + \chi_9 S^3\right) + \frac{1}{2}\left(\chi_4 SE^2 - \chi_7 S^2 E\right)\end{aligned} \tag{4}$$

and dominant nonlinear coefficients, for aluminum nitride (AlN) being

$$\varphi_5/2e = -8.5, \tag{5}$$

$$\frac{c_3^E}{6c^E} = -18.5. \tag{6}$$

It is important to mention that these nonlinear terms are dominant within the pass-band, and thus other terms could be dominant out-of-band, as the fields' distribution change. However, they are correct when simulating nonlinearities with driving signals within the pass-band.

Finally, following the Mason model derivation, including the nonlinear terms, proposed by [8], one can find the two nonlinear sources that can implement all nonlinear contributions:

$$T_C = \Delta T + \frac{e}{\varepsilon^S}\Delta D\,, \tag{7}$$

$$V_C = \frac{\Delta D}{\varepsilon^S}\,. \tag{8}$$

The nonlinear sources can be added in the elemental cell implementation of the piezoelectric layer.

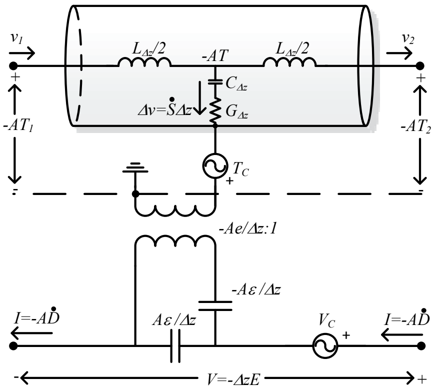

Fig. 2. Circuit model implementation of an elemental cell of the piezoelectric layer. Both mechanical and electrical domains are shown, as well as the electro-acoustic coupling and the nonlinear sources *Tc* and *Vc*.

2.2 BST Capacitor

Ferroelectric materials are well known for their high permittivity values, what makes them good candidates for applications where small footprint is required. On the other hand, the permittivity is nonlinear and thus changes with the electric field, therefore being a desirable attribute for tunable applications [9] or a major drawback when high linearity is a requirement.

The samples being used for this work consist on a 240 nm thick $Ba_{0.7}Sr_{0.3}TiO_3$ sandwiched between two metal electrodes on top of a 500 nm SiO_2 layer. The bottom electrode is made of a 200 nm platinum (Pt) layer, sputtered over a thin (10 nm) TiO_2 adhesion layer, to prevent oxygen leakage from the ferroelectric and to resist the high temperatures for BST deposition. The top electrode is a 350 nm gold (Au) layer with an adhesion layer of Ti (20 nm).

2.2.1 Modeling

Electrical characterization has been carried on-wafer, at LETI, for the fabricated samples by use of a network analyzer. Results are summarized in Fig. 3.

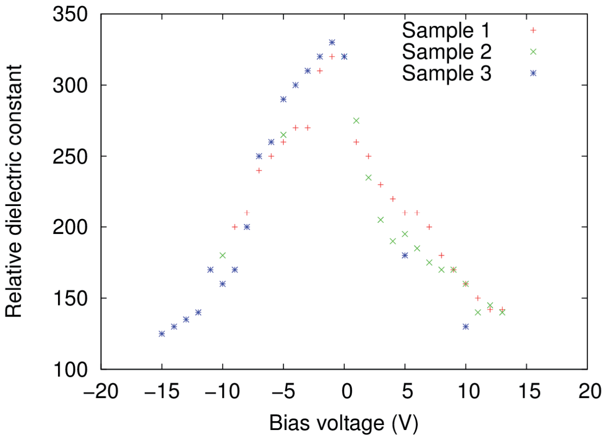

Fig. 3. Extracted dielectric constant vs. bias voltage.

De-embedding the parasitic capacitance of the SiO_2 and Si substrate, for different applied voltage levels, allows for an accurate description of the permittivity dependence on the electric field, as follows [10]:

$$\varepsilon(E) = \frac{\varepsilon(0)}{2\cosh\left(\frac{2}{3}\sinh^{-1}\left(\frac{2E}{E_{1/2}}\right)\right) - 1} \tag{9}$$

with $\varepsilon(0) = 320$ and $E_{1/2} = 3.5\ 10^7$ V/m. On the other hand, the loss tangent is not smaller than $\tan\delta = 0.02$, what leads to an electrical model in Fig. 4, with $R = 2$ kΩ. This is the capacitor model that will be used to implement the filter in the circuit simulator.

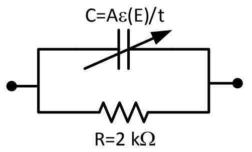

Fig. 4. Electrical circuit model of the BST capacitor; the model includes a purely low-loss capacitance whose permittivity changes with the electric field and the corresponding dielectric losses.

2.3 Filter

The topology of the filter is of a lattice type, with the particularity that the crossed resonators are replaced by the BST capacitors. For applications where a very wide bandwidth is not required this solution might be enough, and has the advantage that the BST capacitors come with a very small footprint compared to the resonators. The area of the resonators and capacitors are set accordingly so that the filter shows a good 50 ohms impedance matching at the central frequency, being $2.24{\cdot}10^{-8}$ m^2 and $1.57{\cdot}10^{-10}$ m^2 respectively. Figure 5 shows the circuit implementation of the filter, and Figures 6 and 7 show the impedance matching at the input and the transmission s-parameters respectively.

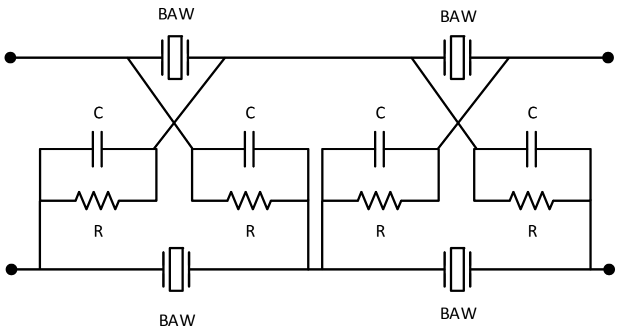

Fig. 5. BAW filter with BST capacitors implementation, of the lattice type, having balanced input and output.

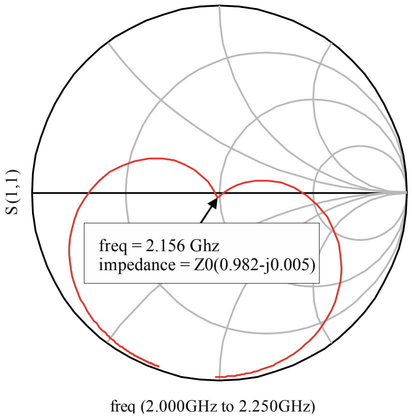

Fig. 6. Smith chart of the simulated input reflection coefficient, showing good impedance matching at the central frequency.

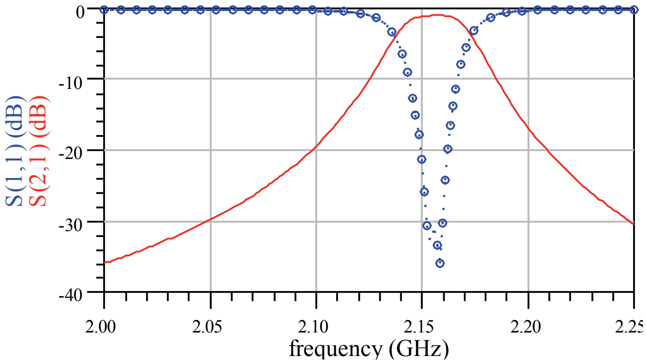

Fig. 7. Simulated transmission S-parameters of the BAW filter, showing a good overall response.

3. Nonlinear Analysis

The requirements regarding the nonlinear behavior of filters are getting more and more challenging as new communication standards require higher levels of linearity to perform properly [1]; and it is expected to get even more challenging when LTE carrier aggregation gets established. In this scenario, it is of a crucial importance to test for the nonlinear behavior at the design stage prior to fabrication, as it avoids unnecessary fabrication iterations.

Specifications usually affect the transmission filters and the entire duplexers, with specific requirements for each. For example, a specific requirement for duplexers is the level of second-order intermodulation distortion and third-order intermodulation distortion that would produce mixing components that would fall within the receiver band, as this would desensitize the receiver. For single filters, the specifications usually affect the generation of spur content that could cause interference in other bands. More specifically, second harmonic, third harmonic and third-order intermodulation distortion.

3.1 Second Harmonic Generation

Second order nonlinearities, resulting in second order intermodulation distortion and second harmonic, are the main issue regarding the nonlinear behavior of aluminum nitride based BAW filters. This arises due to a piezoelectric constant that changes with the strain [7]. While this is true for single ended filters, it is not a concern for balanced filters, where the second harmonic is cancelled at the output. This is also the case for the filter under study as shown in Fig. 8.

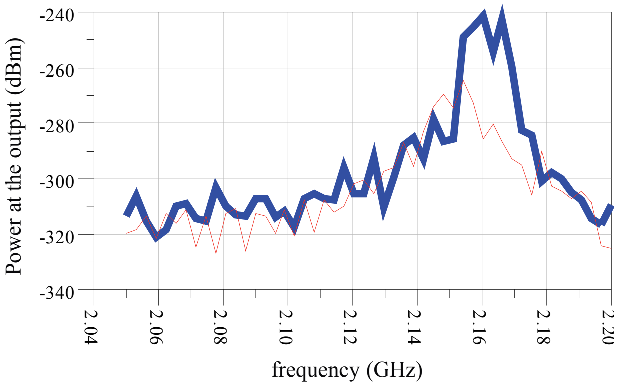

Fig. 8. Simulated second harmonic response at the output for the filter for all nonlinear contributions active (thick line), and for only the BAW resonators active (fine line). Input power is set at +25 dBm.

3.2 Third Harmonic Generation

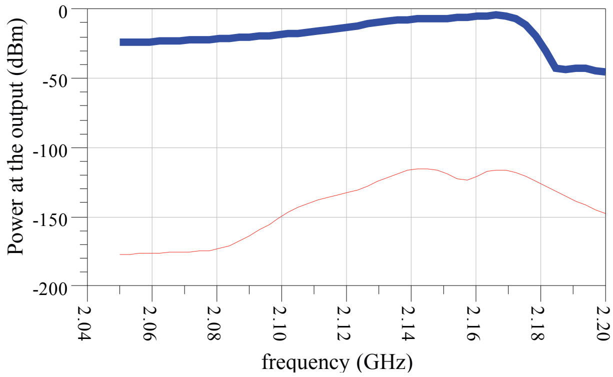

Fig. 9. Simulated third harmonic response at the output for the filter for all nonlinear contributions active (thick line), and for only the BAW resonators active (fine line). Input power is set at +25 dBm.

The levels of third harmonic generated from regular AlN based filters are usually not that critical when compared to the levels of second harmonic [11]. On the opposite, it is well known that ferroelectrics exhibit a strong quadratic nonlinear response given its inherent tunable nature [5]. This is confirmed by the simulations presented here, in Fig. 9, where a very strong third harmonic is obtained, with a maximum equivalent OIP3 of +42.5 dBm. For the same level of input power, the same filter with BAW resonators instead of BST capacitors, would show a level around -100 dBm.

3.3 Third-Order Intermodulation Distortion

Finally, the third-order intermodulation distortion is simulated, by use of two balanced tones with a separation of 10 MHz at +25 dBm, showing extremely high levels, with a maximum equivalent OIP3 of +32.5 dBm. This would degrade the overall signal quality, as it produces spectral regrowth, and can potentially produce spur signals that negatively impact on neighbor bands or other devices on the radiofrequency path. For a regular lattice filter, with no BST capacitors, the level of third-order intermodulation distortion would be around -60 dBm.

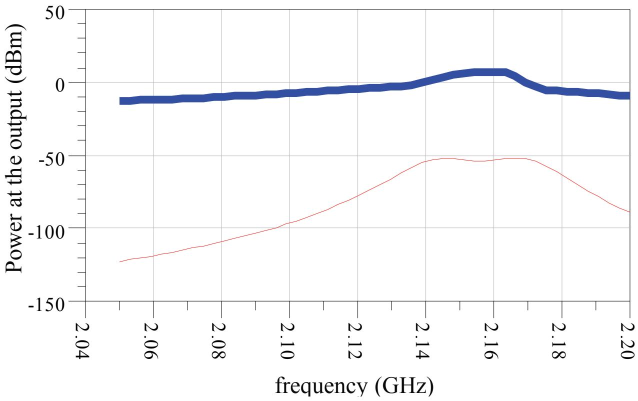

Fig. 10. Simulated third order intermodulation distortion response at the output for the filter for all nonlinear contributions active (thick line), and for only the BAW resonators active (fine line). Input power is set at +25 dBm. The central frequency is swept in a two tone test.

4. Conclusions

Second harmonic, or in general, second-order nonlinearities is the problematic aspect in regular AlN based BAW filters, while third-order nonlinearities are usually not a special concern. On the contrary, for BST-based filters we see very high levels of third harmonic and third-order intermodulation distortion content. This would create serious doubts about the viability of tunable filter solutions based on ferroelectric materials like BST. Therefore, a nonlinear analysis would be of a crucial importance in those cases, and its filter applications probably limited to reception filters not being part of any duplexer.

While still more progress has to be done on testing this technology with other topologies, or even cancellation techniques, this work on a specific design shows nonlinear levels too high for a regular commercial filter. Therefore, exploring other high permittivity materials, not of a ferroelectric nature, that could still offer a miniaturization advantage without the high nonlinear response, would be a smarter alternative.

Acknowledgements

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Eduard ROCAS received the Telecommunication Engineering degree and Ph.D. degree from the Universitat Politècnica de Catalunya (UPC), Barcelona, in 2005 and 2011 respectively. From September 2005 to July 2006, he was involved in the simulation and modeling of advanced SONARs at the Computer Vision and Robotics Group (VICOROB - University of Girona) as a FPU Grant Holder. From January 2009 to July 2011 he was a Guest Researcher at the National Institute of Standards and Technology (NIST), Boulder, CO, working on materials characterization and modeling for microelectronic devices. Since July 2011 he is with UPC as a Research Engineer working on the design of advanced instrumentation and electro-acoustic devices. Dr. Rocas was the finalist of the XXXII Prize for the best doctoral thesis in Defense by COIT (Colegio Oficial de Ingenieros de Telecomunicación) and the recipient of the Extraordinary Award for the best doctoral thesis in Information Technologies and Communications by UPC. Dr. Rocas is also the recipient of a Postdoctoral 2011 Beatriu de Pinós fellowship from the Catalonia Gov. (European Union - Marie Curie co-funded Actions).

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Carlos COLLADO received the Telecommunication Engineering and Ph.D. degrees from Universitat Politècnica de Catalunya (UPC), Barcelona, in 1995 and 2001, respectively. He also holds an M.S. on Biomedical Engineering (2002). In 2001 he was awarded with the Prize to the best doctoral thesis in Electronics and Telecommunications area from UPC. He joined the faculty at UPC in 1998, and he became an Associate Professor in 2005. Since Nov-2005 to Jan-2008 he was a vice-dean of the Technical

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Jordi VERDU was born in Sabadell, Spain, in 1980. He received the Telecommunications Engineering degree in 2006, the M.S. degree in 2007 and the Ph.D in 2010 from the Universitat Autònoma de Barcelona. His research topics are focused in the design of microwave devices and also filters based on acoustic resonators.

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Alexandre REINHARDT obtained his Engineering Degree from the Ecole Centrale de Lille (France) in 2001 and his Master Degree in Ultrasonics & Telecom from the Valenciennes Univ. (France) the same year. In 2005, he received a Ph.D in Engineering from the Franche-Comté Univ. (Besançon, France). He then joined the University of Bath as a post-doc, to study acousto-optic interactions in porous silicon multilayers. Since the end of 2006, he works as a Research Engineer at CEA, LETI where he is involved in the simulation and design of acoustic resonators and filters, mostly BAW devices and on the investigation of novel acoustic solutions for RF architectures.