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 ε_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.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN</td>
<td>200 nm</td>
</tr>
<tr>
<td>Mo</td>
<td>250 nm</td>
</tr>
<tr>
<td>AlN</td>
<td>1000 nm</td>
</tr>
<tr>
<td>Mo</td>
<td>250 nm</td>
</tr>
<tr>
<td>SiO2</td>
<td>1000 nm</td>
</tr>
<tr>
<td>W</td>
<td>500 nm</td>
</tr>
<tr>
<td>SiO2</td>
<td>500 nm</td>
</tr>
<tr>
<td>W</td>
<td>800 nm</td>
</tr>
<tr>
<td>SiO2</td>
<td>500 nm</td>
</tr>
<tr>
<td>Si</td>
<td>725 μm</td>
</tr>
</tbody>
</table>

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 en-
ables 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.

![Piezoelectric layer implementation](image)

**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

\[
T = c^E S - e E + \Delta T_{NL},
\]

\[
D = e S + \varepsilon^S E + \Delta D_{NL}
\]

with \(T, S, E\) and \(D\) being the stress, strain, electric field and displacement field respectively and \(c^E, e\) and \(\varepsilon^S\) the elasticity, piezoelectric coefficient and permittivity. The nonlinear terms \(\Delta T_{NL}\) and \(\Delta D_{NL}\) are:

\[
\Delta T_{NL} = \frac{1}{2} \left( c^E S^2 - \varphi_S E^2 \right) + \varphi_S SE
\]

\[
+ \frac{1}{6} \left( e^S S^3 - \varepsilon^S E^3 \right) + \frac{1}{2} \left( \chi_S SE^2 - \chi_S S^2 E \right)
\]

\[
\Delta D_{NL} = \frac{1}{2} \left( e^S E^2 - \varphi_S S^2 \right) + \varphi_S SE
\]

\[
+ \frac{1}{6} \left( \varepsilon^S E^3 + \varepsilon^S S^3 \right) + \frac{1}{2} \left( \chi_S SE^2 - \chi_S S^2 E \right)
\]

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

\[
\varphi_S/2e = -8.5,
\]

\[
\varepsilon^S/6e = -18.5.
\]

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:

\[
T_c = \Delta T + \frac{e}{e_S} \Delta D,
\]

\[
V_c = \frac{\Delta D}{e_S}.
\]

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

![Elemental cell implementation](image)

**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 \(T_c\) and \(V_c\).

### 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 Ba0.7Sr0.3TiO3 sandwiched between two metal electrodes on top of a 500 nm SiO2 layer. The bottom electrode is made of a 200 nm platinum (Pt) layer, sputtered over a thin (10 nm) TiO2 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.
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]:

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

with $\varepsilon(0) = 320$ and $E_{1/2} = 3.5 \cdot 10^7$ 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 $R = 2$ k$\Omega$. This is the capacitor model that will be used to implement the filter in the circuit simulator.

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.

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.

3.2 Third Harmonic Generation

The levels of third harmonic generated from regular AIN 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.

4. Conclusions

Second harmonic, or in general, second-order nonlinearities is the problematic aspect in regular AIN 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.

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References


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