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Process and Design Challenge for SMR-type Bulk Acoustic Wave (BAW) Filters at Frequencies Above 5 GHz

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***Abstract*—With the new 5G wireless communication standard on the horizon, new and formerly unused bands will be introduced with frequencies up to 6 GHz. BAW filters play a crucial role supporting those bands due to their tight guard-band and steep rejection requirements. This paper will elaborate on process and design challenges based on a 5.2GHz filter design.**

Keywords—bulk acoustic wave resonators, high frequency, challenges, piezoelectric

I. Introduction

Over 150 operators in 66 countries around the world are actively testing the new wireless communication standard 5G according to reporting from the global mobile suppliers association, with many having announced release intention beginning as early as 2019. With this standard a new, previously unused spectrum of high frequency bands is introduced (e.g. n77-n79, UNII-1-3) that belongs to frequency group 1 (FR1) and is also referred to as new radio bands. Tight guard-bands among those bands and the requirement for small form factors make this an ideal application for BAW filters due to their compact size, steep transitions and low out-of-band rejection. These requirements however also present novel process and design challenges from a manufacturer's standpoint. For instance, in SMR-type resonators, the layer thicknesses are inversely proportional to frequency (i.e. they scale with 1/f). Consequently, frequency sensitivity to layer thicknesses are high and nominal impedance (50 Ohm) resonator sizes are small (see Fig. 1), thus making deposition and frequency accuracy on one hand and clever layout and routing for power handling and current crowding on the other hand a major challenge. On top of that, thin layers also have intrinsically higher resistive losses, requiring the use of highly conductive materials in order to keep quality factors (Q) high.

This paper will discuss how to overcome some of these challenges in the context of a 5.2GHz filter design.

II. Challenges

This section is subdivided into 4 parts with each one trying to focus on one of the crucial aspects to be taken into consideration when designing a high frequency, high performance, piezoelectric transducer capable of fulfilling tight customer specifications for the 5G wireless communication market.

A. Accoustic and electric losses

Resonator losses are usually subdivided into two main categories: acoustic and electric losses.

Electric losses are heavily influenced by the electrode thicknesses. For piezoelectric type transducers those electrode layers scale with frequency (1/f), meaning for high frequencies they are thin, leading to high resistive losses. It is therefore important to use highly conductive materials usually involving copper, silver or others equally high in conductivity to keep resistive losses low. However, most often those highly conductive metals have low acoustic impedances, directly degrading the performance (Q) of the resonator.

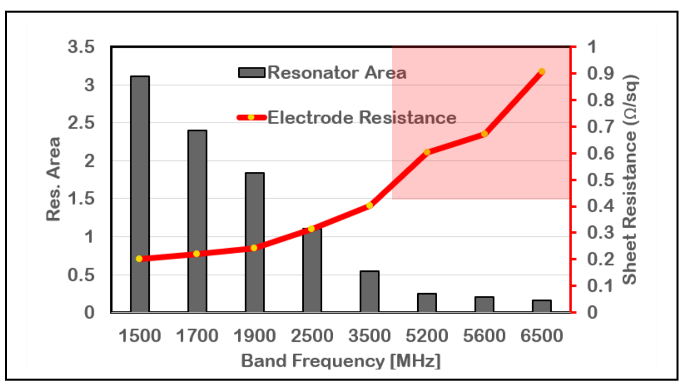

Fig. 1. Relation of resonator area and sheet resistance as a function of frequency. With higher frequency, nominal impedance (50Ohm) resonator sizes get smaller and resistive losses increase.

Common materials like Tungsten or Molybdenum for instance have very high acoustic impedance but low conductivity. Generating multi-layer electrodes combining high acoustic impedance materials with high conductive materials can serve as a compromise between both competing factors [1]. Depending on device performance requirements, a trade-off may have to be struck between acoustic impedance and conductivity.

Acoustic losses on the other hand are more complex and are most often further sub-categorized into viscous, thermo-elastic and scattering losses scaling similarly with frequency as described earlier [1]. Viscous and scattering losses are easier to simulate using FEM, while energy loss through thermo-elastic dissipation (TED) is harder to implement. Some studies are known modeling those losses [2, 3, 4]. The transducer area scales with frequency, making the resonators very small at 5.2 GHz. A common solution to this problem is cascading resonators in series, which increases the size but also the lead length necessary to connect them. A negative side effect of this cascading is that resistive losses increase alongside. It is therefore paramount to keep the lead length to a minimum or add highly conductive materials in lead areas which can help reducing losses. Generation of lateral modes at material boundaries directly influences transducer performance. A common method to mitigate this effect is by implementing a border ring on the edge of the active area. Suppressing or reducing the generation of lateral modes is a large challenge for SMR-type transducers.

B. *Die size and power handling*

With the complexity of modules increasing steadily year over year (i.e. number of bands per module), die size is an important factor to take into consideration. One way of shrinking die size is to include IO vias into wafer level packaging structures. Another way is to keep the area needed to separate dies (saw streets) minimal. Conventionally, mechanical saws are used to separate dies. By using more advanced techniques like laser dicing, die separation structures can be further minimized.

Another important factor when designing a filter at 5.2GHz is the power handling capability. With resonators being small, the power density in each resonator is high which may lead to device failure if the applied power is too high. One common way to reduce this effect is by cascading resonators, which comes with disadvantages mentioned before but may be necessary to meet power handling requirements. For SMR-type resonators there are two main heat paths: through the Bragg reflector and through the over mold housing. High frequency resonators have thin reflector layers which favors heat extraction vertically. In addition, non-electrical vias can be added to help heat extraction.

C. *Piezoelectric coupling requirements*

5G introduces some ultra-wide bands with fractional bandwidth's that can be as large as 24 %. This mandates high coupling materials to realize bandwidth and return loss. While some examples for wide bands like full B41 have been demonstrated with a relatively low coupling material like AlN, a trade-off between return loss and out of band rejection needs to be made [6]. Lower out of band rejection is especially harmful if carrier aggregation is desired. When designing large bandwidth filters, a Sc doped AlN can be used which increases the material coupling significantly compared with the non-doped material. Growth conditions become more challenging for those materials but can be helped with proper seed conditions [7]. In addition, controlling the stress of the piezoelectric material can help to further increase coupling. High stress can however lead to material cracks, decreasing device performance significantly. Therefore, a trade-off between coupling and stress needs to be made.

Another factor to consider is the passivation layer necessary for SMR-type resonators to protect the surface and especially electrodes from corrosion. A typical passivation material is SiN which decreases coupling. In general, but even more so at 5.2 GHz where sensitivities to that layer are high, it plays an important role to keep the passivation layer thickness as small as possible to keep the effective coupling high.

D. *Manufacturing and temperature margins*

With afore mentioned design and process specifics and the fact that many layers at high frequencies have a high sensitivity (i.e. small thickness shifts cause large frequency shifts), it becomes clear that process margins need to be tight. This encompasses all aspects of the manufacturing process, including allowed misalignment margins, deposition accuracy, etch stop capability and trimming. To get the filter to the right frequency and bandwidth position, trimming plays the most crucial role. Proper metrology input and trim accuracy down to single nanometers are necessary.

Another important factor to consider is the temperature sensitivity (i.e. how much does the filter shift with temperature). SMR-type resonators involving SiO_2 are in a good spot due to its positive temperature expansion coefficient counteracting on other materials with opposite expansion coefficient keeping temperature shifts low. The compensation effect can be further improved by doping the material with fluorine [7].

III. Filter Design and Measurements

Filter design at high frequencies requires high precision modelling to achieve minimal passband insertion loss, return loss and desired out of band rejection. Typically, the model can be generated by extracting resonator performance parameters from manufactured devices. This allows to accurately capture piezoelectric and electromagnetic effects in full EM simulations. A reiterative check of device performance and extraction of device performance is crucial to verify the model's accuracy. Qorvo's simulation models have matured to a point that allows resonator performance and filter response prediction without deriving it from manufactured filters. This allows a cost and time saving approach to filter design. At 5.2 GHz it is especially important to also take parasitic coupling effects from the laminate into account to get an accurate picture of the filter response.

Based on Qorvo's latest model, a 5.2 GHz filter was designed and manufactured. Fig. 2 shows a comparison of simulation and measurement results. Across a wide frequency spectrum, a precise match between simulation and measurement was achieved, validating the accuracy of the model used during the design phase. The passband insertion loss at the band edges of 5170 MHz – 5330 MHz is better than 1.4 dB which is up to 0.8 dB better than other currently available parts. Over temp and manufacturing margin, the insertion loss is better than 1.7 dB. Rejection in the range from 5490 MHz – 5850 MHz is better than 60 dB, which outperforms other commercially available BAW parts by more than 10 dB. Return loss across the whole bandwidth is better than 14 dB (see Fig. 3) which translates into at least a 2 dB improvement over comparative devices on the market.

In addition to before mentioned advantages, Qorvo's filter also exceeds specifications for power handling and does not need any external matching components. This is important as it saves the customer space and cost. Qorvo's filter footprint is 1.7x1.1 mm^2, making it significantly smaller than any other available solution (see Fig. 4).

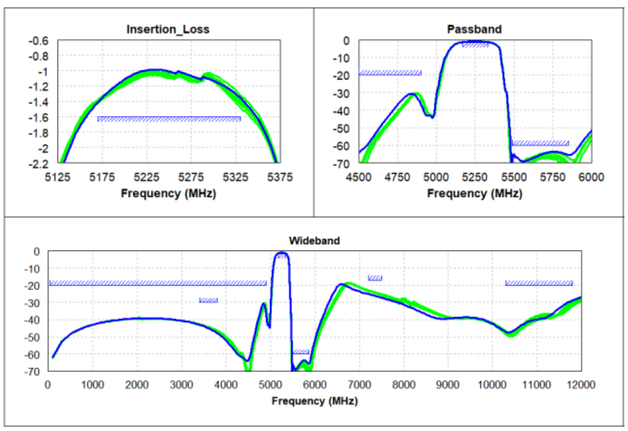

Fig. 2. Comparison between simulation (blue) and measurements (green) of over molded modules. Top left shows passband response with insertion loss at band edges better than 1.4 dB. Over temp and manufacturing margin this translates into better than 1.7 dB. Top right shows narrow band response with rejection better than 60 dB in the region 5500 MHz – 5850 MHz. Bottom shows wide band rejection with overall excellent match between measurement and simulation.

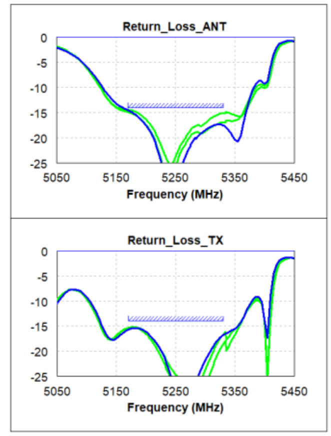

Fig. 3. Comparison of returnloss between simulation (blue) and measured devices (green) on the antenna side shown on top and TX side on bottom. Both sides are significantly better than 15 dB across the frequency range of 5170 – 5330 MHz.

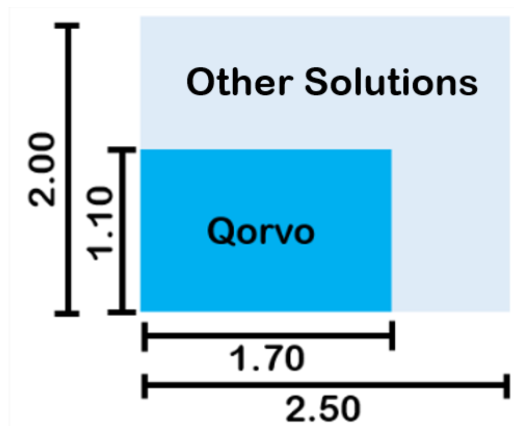

Fig. 4. Comparison of Qorvo's filter package with available parts from competitors. The overall filter package area is approximately 63% smaller.

IV. Summary

The upcoming 5G wireless communication standard is on the horizon and with that new high frequency bands are added to the current used spectrum. These new bands create new challenges for the manufacturing process and design of SMR-type BAW filters. This paper outlined some crucial aspects of these challenges based on the example of a 5.2GHz filter. This filter was designed based on Qorvo's models that allow resonator and filter performance prediction without extraction from physically manufactured material which allows fast and cost efficient filter design. As a result, the manufactured filters are superior in all aspects like size, power handling, insertion loss, and rejection parameters when compared with alternative acoustic filter designs.

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