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Analysis of Border Ring Modes on SMR-BAW Resonators

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***Abstract*—An equivalent circuit model is proposed in order to model the Border Ring (BR) spurious modes on Type I Solidly Mounted Resonators (SMR) BAW resonators and the cancellation of the in-band lateral modes that the BR frame produces. The model has been validated through FEM simulations and with measurements of resonators. It predicts the electrical response of the BR effects for different resonators and BR sizes.**

Keywords—Bulk Acoustic Wave, resonator, Border Ring, lateral modes, circuit model.

I. INTRODUCTION

Lateral modes due to Lamb waves have been a subject of concern regarding BAW resonators, being the main cause of spurious resonances of high-Q resonators. These spurious resonances could lead to a bandpass degradation of the filters, unacceptable by the stringent requirements of mobile RF front-ends.

The Border Ring (BR) technique is an extended spurious resonances suppression method for BAW resonators with Type I dispersion behavior [1], [2]. The main drawback of this technique is that the BR frame generates spurious modes that get coupled below resonance.

The aim of this work is to give insight of the causes that generate the BR spurious modes. The method presented below, is based on our previous work [3] and modifies the previous model to introduce the BR effects. The developed model allows to predict the BR modes and gets into its cause.

II. LAMB WAVES ON SMR

Acoustical wave propagation on BAW resonators is a rather complex phenomenon. Since thickness dimensions are significantly smaller than the resonator lateral dimensions, the entire resonator can be considered as a waveguide.

On a plate, Lamb waves arise due to the coupling of longitudinal and transverse waves at the interfaces of the sheet.

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The mathematical treatment of lamb waves for a nonpiezoelectric isotropic plate is developed in [4] and [5]. Although a mathematical description of this kind of waves exists, there are not analytic expressions for the dispersion curves of each propagating mode into the plate.

A. Dispersion curves

The phase constant β of a Lamb wave propagating in the lateral dimension through a plate of finite thickness (defined in the x-axis and the z-axis respectively) must fulfill the Rayleigh-Lamb equation [5]:

$$\frac{\omega^4}{V_T^4} = 4q^2\beta^2\left(1 - \frac{p\tan\left(pt/2+\alpha\right)}{q\tan\left(qt/2+\alpha\right)}\right) \quad (1)$$

where $p^2 = \omega^2/V_L^2 - \beta^2$, and $q^2 = \omega^2/V_T^2 - \beta^2$. V_L and V_T are the phase velocities of the longitudinal and transverse waves, respectively. Symmetric modes correspond to those with $\alpha = 0$, while antisymmetric ones to those with $\alpha = \pi/2$.

The solutions of (1) can be represented with the dispersion curves. Each mode that propagates through the plate can be characterized by means of its dispersion curve and its cutoff frequency. As explained on [6], only the symmetric modes couple into the resonator's electrical response, so the model only needs to focus on them. The dispersion behavior depends of the relation of the longitudinal and transverse velocities. The curve of the TS2 mode appears above or below the curve for the TE1 mode according to whether V_T is higher or lower than $V_L/2$. Resonators with the TS2 mode below have Type I dispersion, otherwise they have Type II dispersion.

These dispersion curves depend of the plate thickness and material properties. On a SMR, the mirror layers have significant impact on the dispersive behavior of the whole resonator [7]. The mirror stack configuration could be used to influence the intrinsic dispersive behavior Type II of the AlN, making it a Type I resonator. On Fig. 1 the dispersion curves of an AlN SMR with a Type I dispersion are obtained from FEM simulations.

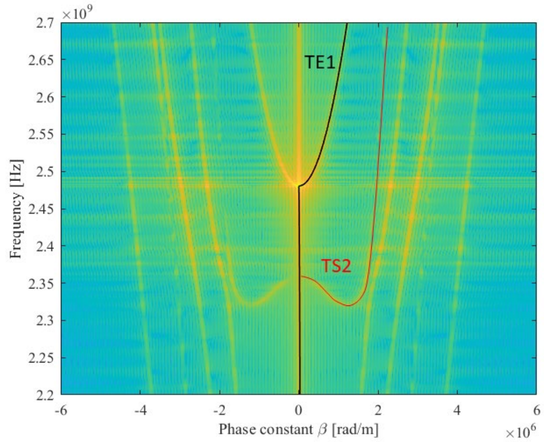

Fig. 1. Dispersion curves of an AlN piezolayer SMR. The fundamental mode TE_1 is fitted to the black curve and the TS_2 to the red one. Type I dispersion behavior can be seen.

III. Border Ring Effect on the Resonator

The main objective of the BR is to suppress the spurious resonances due to the lateral modes in a BAW resonator [1]. The idea behind, is to generate a region outside the resonator with a real phase constant, and an imaginary phase constant outside. This way the energy is trapped and constant displacement boundary conditions are fulfilled at the two interfaces. The BR consists in a thickness-increased area around the perimeter of the resonator. The width W of that framed area must fulfill [1]

$$\beta_b \tan\left(\beta_b W\right) = \beta_o, \tag{2}$$

where β_b and β_o are the phase constants of the BR, and the outside area respectively.

A. Border Ring Modes

Due to the increased thickness of the BR area, it resonates at a lower frequency than the resonator's active area. The electrical response of the resonator can be expected as having two shunted resonators of different thickness, adding another

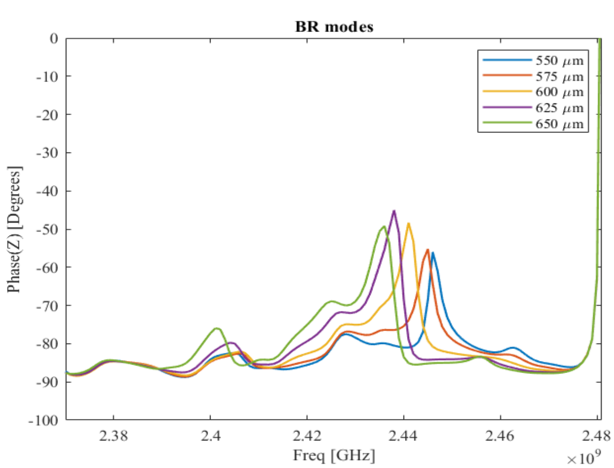

Fig. 2. Different BR modes depending of the BR width (from 5.5 µm to 6.5 µm).

resonance below the main one. However, FEM simulations and measurements show something else. On Fig. 2, it can be seen how it does not appear a single resonance for the BR mode.

Depending of the width of the BR, more or less resonances appear in a quite unpredictable way. That phenomenon suggests that the multiple resonances are due to a lateral mode propagating, not only under the BR area, but also under the active area. This mode is manifested in the resonator's electrical response when the coupling in the thickness direction is high and that happens under the BR area, since the cut-off frequency of the TE1 mode is lower for the BR section than the one for the active section. These low cut-off modes, which are responsible of the BR spurious modes, can be seen on Fig. 1, below the TS2 mode.

As an example, FEM simulations of an SMR-BAW resonator show that acoustic resonances below the cut-off frequency of the fundamental mode of the active area exist through the whole structure. This mode can be seen in Fig. 3, where the displacement pattern at one of the BR resonant frequencies is shown.

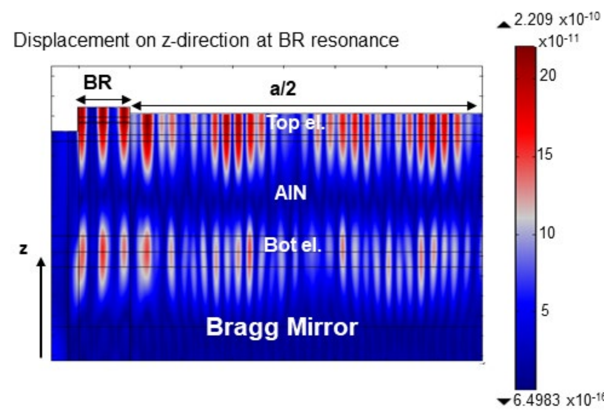

Fig. 3. FEM simulation of a SMR. The displacement field on the thickness direction is shown.

IV. Proposed Model

In order to validate the low cut-off propagating mode origin of the BR resonances, a simplified circuital model based on the one described in [3] is proposed.

A. Previous lateral modes model

The Mason's based model presented on [3] is able to reproduce the lateral modes on a BAW resonator given its dispersion curve. It consists on a lateral dispersive transmission modeling the lateral dimension of the resonator coupled to the Mason model of the resonator. FEM modeling and measurements were in very good agreement with the circuit model [3]. Nevertheless, the model described in [3] did not include the BR frame.

B. BR modes modification

In order of being able to model the BR modes, a modification of the previous model is proposed. The fundamental concept behind it remains in the naive initial idea that the response of the BR on a BAW resonator will resemble to two shunted resonators of different thicknesses. One can think of placing two Mason models in parallel, but there will be only a single and narrow resonance for the BR instead of the multiple resonances that appear on FEM simulations and measurements. This is because the conventional Mason circuit only models for the propagation in the thickness direction

The proposed model consists on using additional dispersive "lateral transmission lines" [3] coupled to each conventional Mason circuit to consider the lateral propagation (Fig. 4). When doing so, special care has to be taken when modelling the lateral propagation. Reference [8] proposes to use different transfer matrices for each resonator section to model the lateral displacement. Each transfer matrix has the phase constant of the dispersion curve of each section. This idea can also be applied to dispersive transmission lines being able to connect the different sections to obtain the displacement profiles. The advantage of using transmission lines over transfer matrices is that they can be used as it was done in [3] without more modifications.

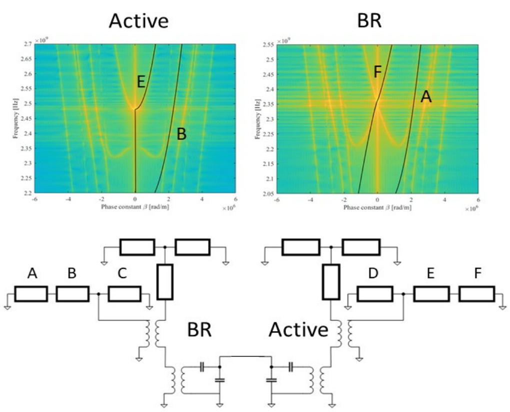

Fig. 4. Circuital model for the BR modes. The dispersion curves correspondents to each lateral transmission line section are shown on top. C and D are lumped resistances.

The last consideration to be done is that the Mason circuit that accounts for the BR section has to consider the dispersive behavior of the TE1 mode. Note that the width of the BR section w_{BR} is typically a few microns, so its main TE1 resonance if the BR was isolated would be slightly higher than its conventional cut-off frequency (piston-mode). This effect is usually neglected when modelling the active area using a conventional Mason model since the length of the resonator is around a hundred of microns, but it cannot be neglected for the very narrow BR section.

Fortunately, this effect can be automatically corrected if the dispersive curve of the BR section is known. This is described in the following subsection IV.C.

The model of Fig.4 results as two Mason models, one for the resonator active area, which accounts also for the cancellation effects of the in-band lateral modes, and other for the BR area, which accounts for the modeling of the spurious resonances below the series resonance. Both Mason models have dispersive lateral transmission lines modeling the different lateral sections of the resonator.

C. Mode Dispersion Relations

For the lateral transmission line belonging to the Mason of the active area, the dispersion curves of the TE1 mode are used both for the active area (curve E in Fig. 4) and for the BR area (curve F in Fig. 4). Regarding to the lateral transmission lines belonging to the BR Mason, the low cut-off modes dispersion curves (A and B in Fig. 4) are selected instead. The outside area is modeled with a lumped resistance (C and D in fig 4) to model the small leakage of the acoustic waves.

The dispersion relations associated to each lateral line shown in Fig. 4 are obtained from FEM simulations of the independent resonators having the stack configuration of the active area or the stack of the BR section. The lateral displacement profile is obtained for each frequency and later a Fast Fourier Transform (FFT) is performed to obtain them. Finally, these curves are fitted using the formulation described in [3].

D. Rectangular Resonators

As done in [3], superposition of modes is used to model 3D resonators. In this case, two lateral lines, one for each direction, with the appropriate lengths are used (not included in Fig. 4 for simplicity of the scheme). This allows to model different aspect ratios.

V. Simulations and Measurements

A. FEM Simulations of SMRs with BR

SMRs with different BR widths were simulated to validate the proposed model. From the same stack, we obtained the dispersion curves shown in Fig. 4. The circuital model was set like in Fig. 4 and adjusted to match two different BR widths of two FEM simulated resonators. Fig. 5 shows the phase of the input impedance of two simulated SMR with different BR widths, and the adjustment of the circuital model proposed.

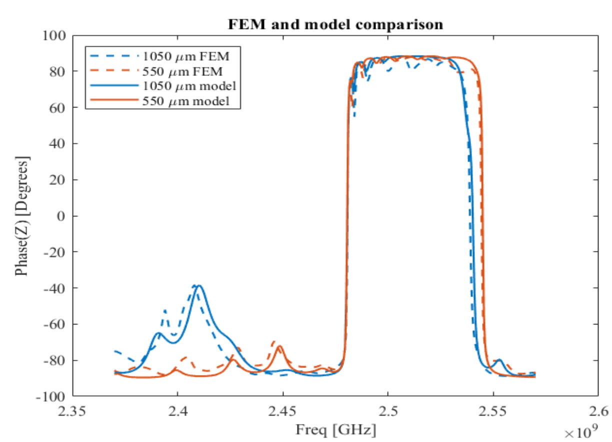

Fig. 5. Phase of the input impedance of FEM simulated SMR (dotted traces), and adjustment of our model (solid traces). Blue traces correspond to a BR width of 5.5 µm, while red to 10.5 µm.

As it can be seen, the current model is not able to perfectly predict the in-band cancellation effect. We believe that is due to the very simplified model that couples the lateral transmission lines in a single point, losing therefore the distributed nature of the coupling. This inaccuracy can be corrected in part if the w_{BR} considered for the in-band cancellation differs a little from the real one. For this example, we have considered w_{BR} of 10.9 µm and 5.21 µm for the in-band cancellation, being the real values w_{BR} 10.5 µm and 5.5 µm respectively.

Despite the simplified coupling mechanism of the lateral transmission lines, the current model can be useful to model, for a given optimum border ring, the BR modes and the in-band lateral modes for different dimensions of the active area and, therefore, different aspect ratios as it is shown in the next subsection V.B.

B. Measurements of SMR resonators with BR

The measured devices were four SMR resonating at 2.48 GHz, with a BR width of 3.5 µm, two different areas ($13\cdot10^{-9}$ m^2 and $6.46\cdot10^{-9}$ m^2), and for each area two different aspect ratios (one square resonator and one rectangular with an aspect ratio of two).

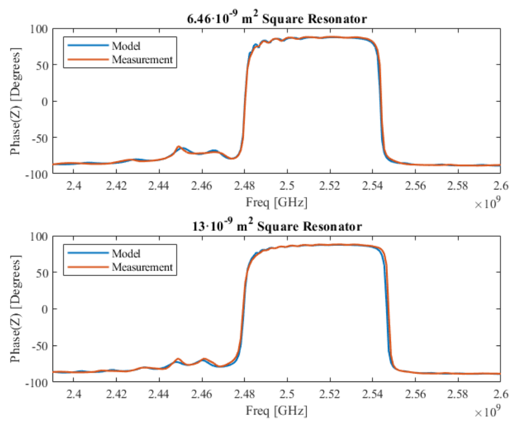

Fig. 6. Phase of the input impedance of the two square resonators.

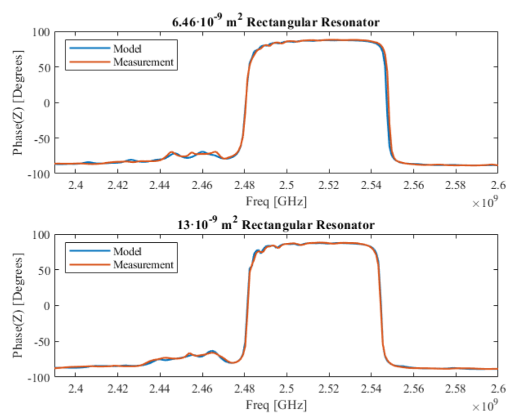

Fig. 7. Phase of the input impedance of the two rectangular resonators

The dispersion curves for the active area were obtained in an experimental way adjusting the dispersion curves to a measured SMR without BR as it was done in [3]. The model was then adjusted to a certain BR width, which can be different for the BR and active section, to match one resonator. The width selected to match the in-band cancellation was 3.5 µm, while the one for the BR resonances was 5.9 µm.

Using the same parameters but the area and aspect ratio, the other three resonators were simulated showing a good match between the circuital model and the measurement (Fig 6 and Fig. 7). It can be seen that once the BR width that provides good agreement with the measurements is found, any change on the area or the aspect ratio of the resonator match the spurious modes suppression and the BR resonances.

VI. Conclusion

The proposed circuit model succeeds in modelling the cancellation effect of the in-band lateral modes due to the BR section and the BR modes, for a given BR width. However, the circuital model fails when simulating the cancellation and the BR mode as a function of the BR width. The main drawback of the model is the coupling of the lateral line at a single point. For resonators without BR there are always a maximum of the stress at the coupling point [3], but for resonators with BR that maximum does not rest at the coupling point in the circuit model. Further research must be performed to avoid coupling the lateral lines at a single point.

Despite its limitation, this model gives strong evidence of the BR resonances origin, laying it in the low cut-off modes propagating through the whole resonator, which are electrically coupled mainly at the BR region. It is also remarkable that the model allows to predict for a given BR width, the cancellation effect and BR resonances as a function of the resonator shape. That is a valuable asset for optimizing the shape dimensions trying to minimize the BR resonances, while keeping good cancellation of the in-band modes.

References

[1] J. Kaitila, M. Ylilammi, J. Ella and R. Aigner, "Spurious resonance free bulk acoustic wave resonators," *IEEE Symposium on Ultrasonics, 2003*, Honolulu, HI, USA, 2003, pp. 84-87 Vol.1.

[2] R. Thalhammer, J. Kaitila, S. Zieglmeier and L. Elbrecht, "4E-3 Spurious Mode Suppression in BAW Resonators," *2006 IEEE Ultrasonics Symposium*, Vancouver, BC, 2006, pp. 456-459.

[3] C. Collado, E. Rocas, J. Verdú, J. Mateu, A. Hueltes and R. Aigner, "A lateral modes model for BAW resonators" *2014 IEEE International Ultrasonics Symposium*, Chicago, IL, 2014, pp. 1497-1500.

[4] B. A. Auld, Acoustic Fields and Waves in Solids, vol. 2, 2nd ed. Malabar, FL: Krieger Publishing, 1990.

[5] D. Royer, E. Dieulesaint, "Elastic Waves in Solids I, Free and Guided Propagation", *Springer,* 2000.

[6] K.Y. Hashimoto, "RF Bulk Acoustic Wave Filters For Communications" Artech House 2009.

[7] G. G. Fattinger, S. Marksteiner, J. Kaitila and R. Aigner, "Optimization of acoustic dispersion for high performance thin film BAW resonators," *IEEE Ultrasonics Symposium, 2005.*, Rotterdam, The Netherlands, 2005, pp. 1175-1178.

[8] T. Pensala and M. Ylilammi, "Spurious Resonance Suppression in Gigahertz-Range ZnO Thin-Film Bulk Acoustic Wave Resonators by the Boundary Frame Method: Modeling and Experiment," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 56, no. 8, pp. 1731-1744, August 2009.