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Calculating Current Distribution in BAW Resonators from Interferometric Measurements

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***Abstract*—In this work we are presenting a method to calculate redistribution currents within the electrodes of a BAW resonator, that are caused by the acoustic deformation of the piezo-electric material. The surface deformation data of the resonators has been recorded with an interferometer capable of measuring the amplitude and phase of surface vibrations in the GHz-range. The local deflection is then fed into a discretized model of the resonator electrodes to calculate the redistribution currents and estimate the accompanying ohmic heating.**

Keywords—electrical network theory, interferometer, ohmic heating, bulk acoustic wave resonators.

I. Introduction

Bulk acoustic wave (BAW) resonators are the basic building blocks of modern microwave filters for mobile communications. The BAW technology enables very small, high performance RF filters for the majority of modern LTE (long term evolution) communication bands. Those filters need to be able to withstand high power. The power dissipated in the filter leads to a temperature increase, which shortens the lifetime of the filter or, in the worst case, results in the immediate destruction. Filters used in base-stations have the highest power requirements [1], but the size constraints are conveniently less demanding. Whereas in handsets the transmit powers are lower, albeit the integration density is much higher [2] and therefore heat generation and operating temperatures become vital parameters that need to be kept in check [3]. Knowing where and how heat is produced is crucial to be able to improve dissipation or effectively reduce the generation of heat in the first place.

Here we focus on heat generated by electric currents in the electrodes of the BAW resonators. Not the overall current, but the part of the current which is generated by the spurious acoustic response of the resonator. The goal was to determine if the redistribution currents between hills and valleys, caused by spurious modes, would lead to significant local heating.

II. Method

A. Deformation induced current

The starting point for the simulation of redistribution currents is the following formula from the book of Rosenbaum [4]:

$$I = j\omega C_0 V + hC_0(v_1 - v_2), \tag{1}$$

with:

$$h = e/\epsilon^S \tag{2}$$

Where ω is the angular frequency, C_0 the static capacitance of the resonator, V the applied voltage, e the relevant components of the piezoelectric matrix and ϵ^S the permittivity at constant strain. The second term, containing the complex surface velocities (v_1, v_2), is the one of interest, since the first term only describes the current through the static capacitance of the resonator, which is not dependent on any acoustic deformation. Considering v_1 and v_2 are the time derivatives of u_1 and u_2, the complex top and bottom surface displacements, and we are dealing with harmonic excitations, we can substitute v_i with $j\omega u_i$.

Furthermore, the assumption is made that the resonator surface displacement is a good estimation of the piezo thickness change. The validity of this assumption is supported by the fact that most of the strain is confined to the piezo layer and the top- and bottom-electrodes are comparably thin. Additionally, only extensional modes of the piezoelectric material will couple to the driving electric field, whereas flexural modes don't change the thickness of the piezo and therefor don't couple to the field and are thus not excited. This leads to the equation for the surface displacement u_S:

$$2 \cdot u_S = u_1 - u_2 \tag{3}$$

The final formula to calculate the current I_{disp} through the piezo from the surface displacement u_S is:

$$I_{disp} = A \cdot u_S \tag{4}$$

Where A contains $j\omega 2hC_0$, which are all known values. As the interferometer measurement data is not giving absolute deflection values, we can treat A as an arbitrary imaginary scaling factor.

B. Discretization into an equivalent circuit

Discretizing the resonator top- and bottom-electrodes as lateral grids of resistors and connecting them vertically via a current source and shunt impedance gives an electrical network as is schematically depicted in Fig. 1. Each electrode grid has as many points as have been scanned in the interferometric measurement. The lateral resistor values (Z_{TE}, Z_{BE}) are derived from the sheet resistivity of the electrodes. The impedance Z_{C0} is equal to $1/(j\omega C_0)$. Z_{load} is the source impedance of the driving signal generator (usually 50Ω). The values I_{disp} for the current sources are derived from the interferometric measurements according to section II.A.

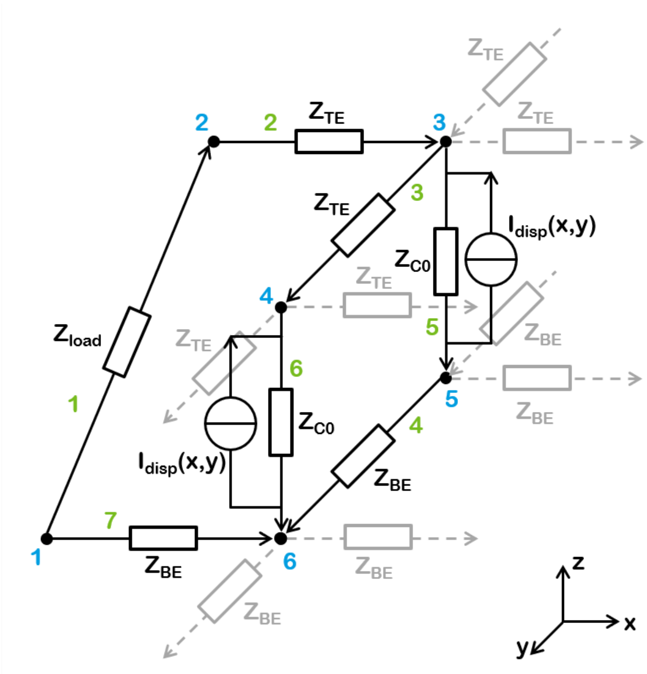

Fig. 1. Schematic representation of the discretisized resonator model. The top- and bottom-electrodes are represented by the top- and bottom layer of Z_{TE} and Z_{BE} resistors, respectively. Z_{C0} is the impedance through the piezoelectric material due to its static capacitance. Z_{load} the impedance of the driving signal source. I_{disp} is the current introduced due to the displacement of each point on the piezo surfaces. The blue numbers show exemplary numbering of nodes, whereas the green numbers denote branches. The grey branches/impedances depict the continuation of the grid in the lateral dimensions to represent the full electrodes.

Every point where two or more elements are connected to each other is called a node and every path between two nodes is a branch. This electrical network representing a BAW resonator can consist of ten- to hundred thousand of nodes and roughly five times that number of branches. To solve this circuit and calculate all currents and voltages, we need to setup a system of equations. This is easiest done by numbering all the nodes and branches (see Fig. 1) and using electrical network theory, graph theory and basic algebra.

C. Electrical network theory, Graph theory and Algebra

Graph theory describes relations of nodes (points, objects) and branches (edges, links, lines) and can be used to map an electrical network onto a so-called directed graph. Using this approach, we can systematically setup a system of equations in matrix form, which is necessary to solve the circuit.

We start, as already mentioned, by numbering the nodes and branches in our electrical circuit. There is no need to use a certain order or system of numbering, but by doing so debugging can be much easier. Next we need to generate an incidence matrix $\boldsymbol{A}$ that describes which branches are outbound/inbound to which nodes. The matrix has one column for each node and one row for each branch. If a branch runs from node a to node b, the row corresponding to that branch has -1 in column a and 1 in column b; all other entries in that row are 0. In most cases this incident matrix will be very sparse. The incidence matrix will be used to convert from node (absolute) voltages to branch (differential) voltages when calculating branch currents.

The impedances of the network branches must be brought into matrix form as well. This is done by generating a diagonal m-by-m admittance matrix $\boldsymbol{Y_b}$ where m is the number of branches. The diagonal elements contain the complex admittance values for each corresponding branch.

Now we need to take care of the correct representation of the displacement induced currents $\boldsymbol{I_{disp}}$. For reasons apparent later, we will construct a current vector $\boldsymbol{I_n}$, that contains one entry per node. All the nodes that connect to one of the current sources will get a current value assigned which is determined by (4). If the current is flowing into the node, we will assign $+I_{disp}$. If it is flowing out of the node, we will assign $-I_{disp}$.

Now we can use those matrices and vectors to solve the full system of equations. First, we convert the branch admittance matrix $\boldsymbol{Y_b}$ to a node admittance matrix $\boldsymbol{Y_n}$ by use of the incidence matrix $\boldsymbol{A}$:

$$\boldsymbol{Y_n} = \boldsymbol{A} \cdot \boldsymbol{Y_b} \cdot \boldsymbol{A}^T \tag{5}$$

Now we can use Ohm's law to write our system of equations in matrix form:

$$\boldsymbol{Y_n} \cdot \boldsymbol{V_n} = \boldsymbol{I_n} \tag{6}$$

This can easily be solved for the node voltage vector $\boldsymbol{V_n}$ by various solvers or by multiplying both sides with the invers of $\boldsymbol{Y_n}$ from the left. We are mainly interested in the currents through the branches of the system, so we need to convert the node voltage $\boldsymbol{V_n}$ in to branch voltages $\boldsymbol{V_b}$:

$$\boldsymbol{V_b} = \boldsymbol{V_n}^T \cdot \boldsymbol{A} \tag{7}$$

And finally:

$$\boldsymbol{I_b} = \boldsymbol{V_b} \cdot \boldsymbol{Y_b} \tag{8}$$

Since the dissipated power in Joule heating is proportional to the square of the current flowing through a resistive element, we can visualize the relative heating distribution in our resonator electrodes by plotting I_b^2.

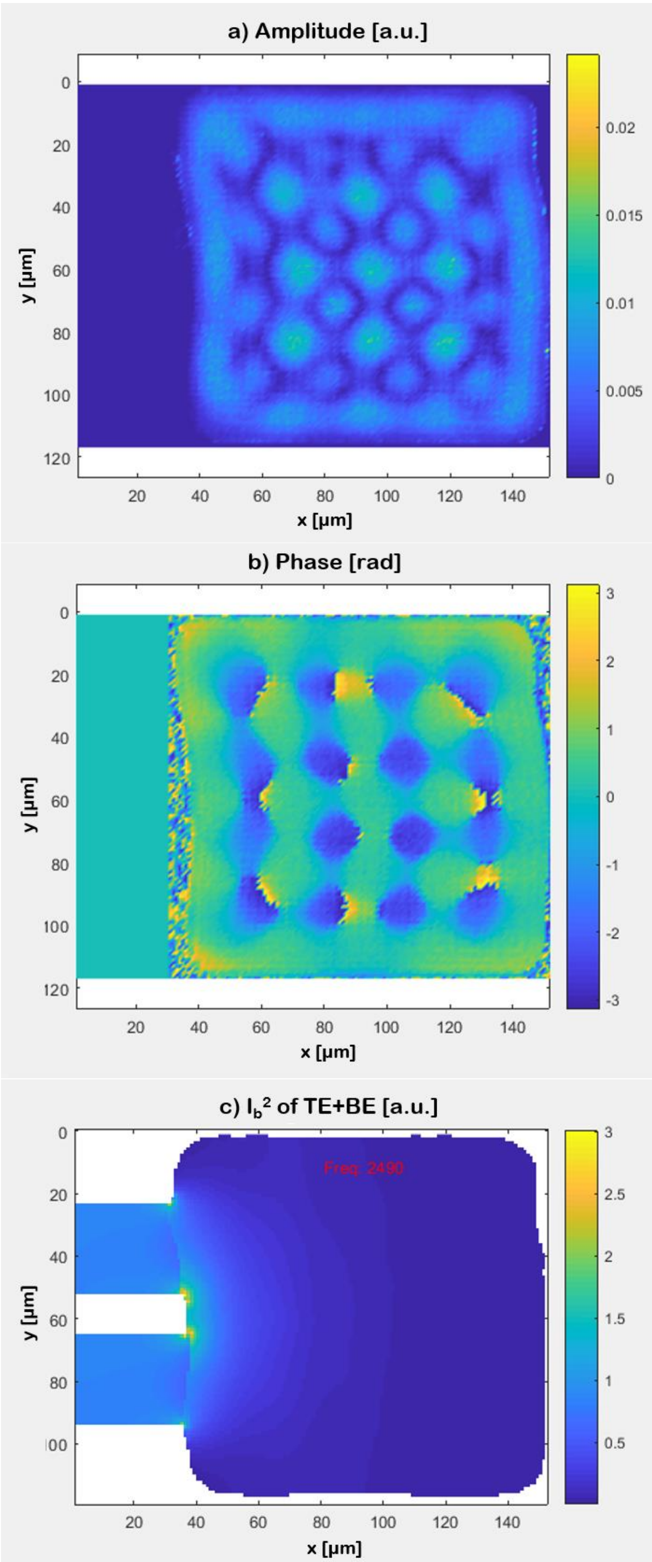

Fig. 2. Interferometric measurement of the displacement amplitude (a) and phase (b) of a BAW resonator at 2.49GHz. c) Superposition of the square of the branch current through the top- and bottom-electrode as calculated from the interferometric displacement measurements. Current crowding on the inside corner where the feed leads merge into the resonator electrodes is visible. No current hot-spots due to spurious modes visible.

III. Results

Fig. 2a shows the displacement amplitude and Fig. 2b shows the phase of a BAW resonator driven at 2.49GHz as measured with the interferometer. The spurious mode pattern of one of the modes below the series resonance frequency f_s can be seen very clearly. Approximately four and a half wavelengths fit into the lateral dimensions of the resonator at this frequency, so there are five hills and four valleys (not counting the basically clamped edge of the resonator). The superposed calculated currents in the top- and bottom-electrodes can be seen in Fig. 2c. Apparently, there are no hot-spots due to redistribution currents between hills and valleys of the surface displacement visible. The current crowding effects around the leads contacting the resonator electrodes contribute much more to local heating effects than any mode pattern related currents.

Additionally, to those current distributions we had a look at the current through Z_{load} (see Fig. 1) over frequency, which represents the driving current from the signal generator minus the current attributed to the impedance from the static capacitance. In Fig 3. we compare this load current to the current calculated from the s-parameter measurement of the resonator. A negative capacitance -C_0 has been added in parallel to the s-parameter file to eliminate the currents through the static capacitance. The overall current shape from the interferometer data fits the electrical measurements very well. All the current variations from spurious modes have been reproduced excellently. By matching the amplitudes of the two measurements, we could even calibrate the scaling factor A from (4) and calculate absolute surface displacements.

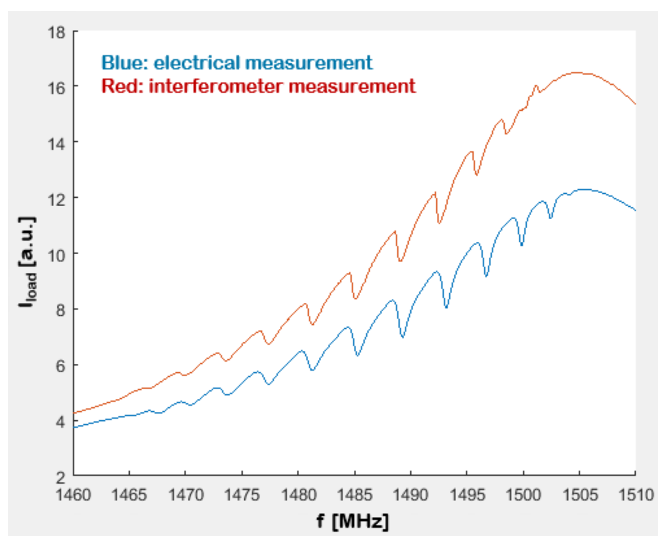

Fig. 3. I_{load} current from a 1.5GHz BAW resonator. Comparison as derived from the interferometric measurement (red) vs. the electrical measurement (blue). The ripple in the current is due to spurious modes developing in the resonators vibrations.

IV. Conclusions

In summary, we have shown that interferometric displacement measurements of BAW resonator surfaces can be used to evaluate "acoustic" redistribution currents in the electrodes. Current crowding on the inner edge of the main current path is reproduced and the idea of hot spots due to excessive currents between deflection hills and valleys was rebutted. Furthermore, the validity of the model was shown by comparison with electrical measurement data from the resonator which has been measured interferometrically.

REFERENCES

[1] J. Galipeau and R. E. Chang, "Design considerations for high power BAW duplexers for base station applications," 2015 IEEE International Ultrasonics Symposium (IUS), Taipei, 2015, pp. 1-4.

[2] G. Fattinger, P. Stokes, A. Volatier, F. Dumont, R. Aigner, “Miniaturization of BAW Devices and the impact of Wafer Level Packaging Technology”, proceedings of IEEE 2013, Prague, June 2013

[3] M. Fattinger, P. Stokes and G. Fattinger, "Thermal modeling of WLP-BAW filters: Power handling and miniaturization," 2015 IEEE International Ultrasonics Symposium (IUS), Taipei, 2015, pp. 1-4.

[4] Joel F. Rosenbaum, “Bulk Acoustic Wave: Theory and Devices”, Artech House, Boston, London, pp. 175, 1988.