FAST SOLVING OF A LINEAR PARAMETRIC MODEL OF A BAW RESONATOR

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Abstract **- A new method for the analysis of a linear parametric A.C. model of a power BAW resonator is presented. A significant shortening of the computation time, in comparison to the APLAC implementation, can be obtained by this way. An example is given for illustration.**

Keywords**:** *BAW resonator, fast analysis.*

1. INTRODUCTION

The use of the digital radio type solutions in the mobile communications is a challenge in the actual microelectronic technology. Because high-power CMOS transistors are not expected to be available in advanced processes within the next several years, the RF front end of the mobile phone will remain analog. In order to miniaturize the mobile phone, the digital part and the analog one can be integrated together as a SiP/SoC system. To this end the BAW (Bulk Acoustic Wave) resonators with AlN like piezoelectric material are one of the best solutions. Being compatible with silicon substrate and processing and significantly cheaper than surface acoustic wave (SAW) [1], the BAW technology has been emerging recently as an alternative solution [2].

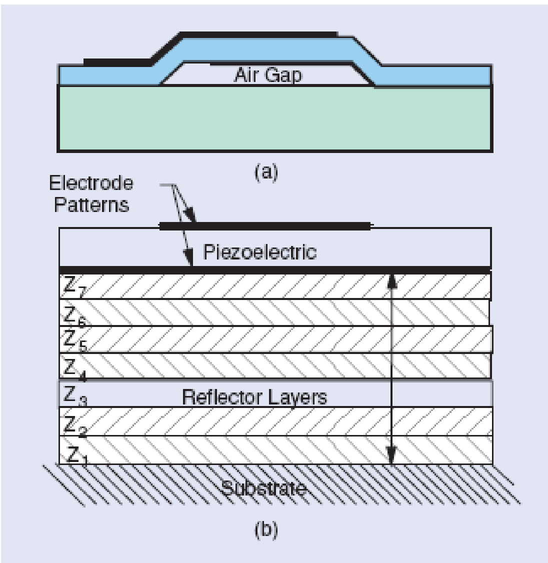

Fig. 1 Thin film resonators. (a)FBAR, (b)SMR

Two types of elementary BAW resonators are produced [3] as it is shown in Fig. 1: solidly mounted resonator (SMR) and acoustic film bulk resonator (FBAR).

The SMR has a resonating structure acoustically isolated from the substrate by a Bragg mirror (a set of alternating high and low acoustic impedance quarter wavelength layers). A FBAR resonator has an air gap (cavity) realized by surface micromachining which isolates the resonating structure. The phenomena in a nonlinear BAW resonator can be analyzed solving a coupled field problem having an electro-mechanical-thermal nature. The terminal nonlinear behavior may be caused by the nonlinear character of one or more field constitutive equations (mechanical, electrical, and electro-mechanical) or by the temperature dependence of some material parameters.

Recently the coupled resonator filter (CRF) has been reported [4]. This filter, used with very good performance in mobile telephony, has two or more mechanically coupled resonators and has the advantage of a less nonlinear behavior than a filter built with SMR or FBAR resonators mechanically uncoupled.

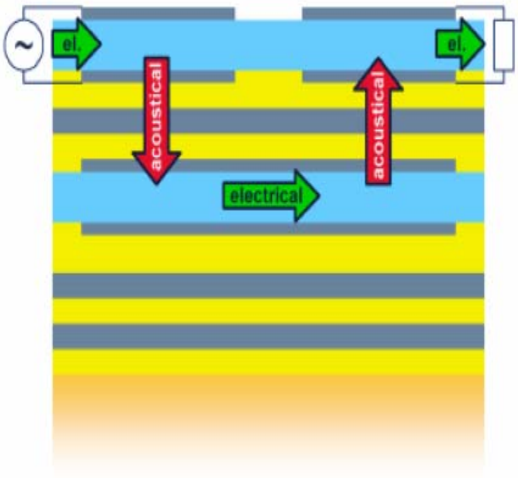

Fig. 2 Coupled resonator filter

Usually the nonlinear behavior of a multi-resonator filter is illustrated by measurements. There are three effects illustrating this kind of behavior:

- the amplitude-frequency effect
- the intermodulation effect

- the bias-frequency effect

the most important being the first one.

Mostly, physical models are proposed in the literature for the nonlinear BAW resonators. These models start from the assumption that one of the constitutive equations mentioned above is nonlinear. Because the coefficients of the Taylor series development of these equations cannot be directly measured, it is very difficult to build a physical model with a large enough range of validity. In spite of this, some impressive agreements are reported between the values calculated with the proposed models and the experimental measurements, these agreements being usually limited to the measurements done by the authors themselves [5]. This is because some behavioral models have been developed starting from measured data only [6].

As the design of the mobile phone analog front end requires the simulation of the power amplifier together with the BAW filters, circuit models for the BAW resonators are very useful. A linear BAW resonator has the same circuit model as a quartz or SAW resonator – the BVD circuit [1]. The most known nonlinear circuit models [7, 8, 6] assume a quadratic dependence of the resistance and the reactance in the motional branch on the r.m.s. current value I, illustrating only the amplitude-frequency effect. The physical models [7, 8] cannot be implemented in a circuit analysis program working either in the time domain or in the frequency domain. The behavioral model in [6] has been implemented in the APLAC simulator using iterative A.C. analyses in order to find the value of the parameter I. This implementation leads to a reduced computation speed due to the subrelaxation factor $\alpha \in [0.2, 1]$ which must be used to ensure the convergence of the iterative A.C. analyses [6].

In this paper a technique for fast analysis of this model is proposed. In Section 2 the behavioral model and the new method for its solving are presented. An analysis example is given in Section 3 followed by a discussion in Section 4.

2. THE MODEL AND ITS SOLVING

In [7] a parametric circuit model of a quartz resonator is proposed (Fig. 3.). Starting from a quadratic dependence of the resonant frequency on the r.m.s. value of the input current I, a constant inductivity and a current dependent capacity are proposed:

$$\frac{1}{C(I)} = \frac{1}{C}(1 + \alpha I^2) \qquad (1)$$

The resistance value is considered as:

$$R(I) = R(1 + \beta I^2)\,. \qquad (2)$$

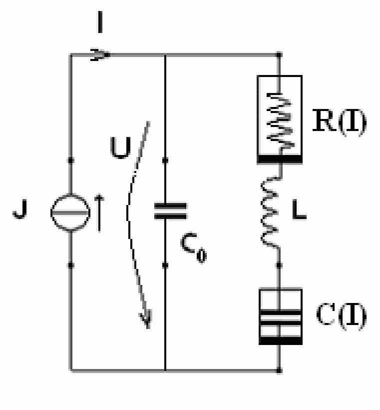

Fig. 3. Parametric circuit model of a quartz resonator [7]

This model gives the correct current dependence on frequency having the input voltage as parameter and the correct resonance frequency dependence on the input voltage (Fig. 4). A 4-th order nonlinearity in the mechanical constitutive equation only is considered in this model. The parameter identification is based on so called "nonlinear constants" involved in the Taylor series development of this equation as well as on the well known formulas of the resonance frequencies and the quality factor.

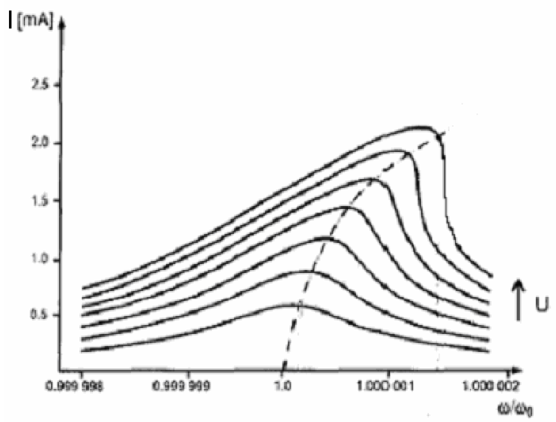

Fig.4. Frequency characteristics of a nonlinear quartz resonator [7]

The family of the frequency characteristics in Fig. 4 is given for $U = U_0 = 0.1V$ and $U = U_0 + k\Delta U$ where $\Delta U = 0.0533V$ and $k = 0,1,...,6$.

A new parameter identification procedure for the model in Fig. 3 based only on the frequency characteristics in Fig. 4 has been developed in [6]. This procedure uses the formulas of the resonance frequencies and the quality factor in the small signal operation together with a least squares estimation of α and β based on the dependence of the series resonance frequency and the resonance current on the input voltage.

The input admittance of the circuit in Fig. 3 is

$$|Y(j\omega)| = C_0\,\omega \cdot \sqrt{\frac{\omega^2 R^2/L^2 + (1/(LC)+1/(LC_0)-\omega^2)^2}{\omega^2 R^2/L^2 + (1/(LC)-\omega^2)^2}} \quad (3)$$

Replacing R and C in (3) according to (1) and (2) a nonlinear equation in *I* can be obtained:

$$f(I) = I - |Y(j\omega, I)| \cdot U = 0 \quad (4)$$

This equation may be solved using the Newton-Raphson procedure:

$$I^{(k+1)} = I^{(k)} - f'^{-1}(I^{(k)}) f(I^{(k)}) \quad (5)$$

These iterations are stopped if a certain error margin ε is reached:

$$\Delta I = \left| I^{(k+1)} - I^{(k)} \right| \le \varepsilon$$

The computation is organized in three cycles:

- the outermost one sweeps the values of the excitation voltage U,
- the following cycle sweeps the frequency interval of interest,
- the innermost one contains the Newton-Raphson iterations.

The analysis starts with an initial value for *I* which is considered null for the first frequency of interest, and corresponds to *I* at the previous frequency in other cases.

3. EXAMPLE

The frequency characteristics in Fig. 4 lead, according to the parameter identification procedure in [6], to the following values: R=165 Ω, L=4.2 H, C=$2.412 \cdot 10^{-16}$ F, C_0=$1.116 \cdot 10^{-10}$ F, α=1.14 A^{-2}, β=$3.405 \cdot 10^5$ A^{-2}.

The procedure described in Section 2 has been implemented in a C code. The frequency characteristics in Fig. 5, whose similarity with Fig. 4 is obviously, are obtained in 10ms for an absolute current error $\varepsilon = 10^{-12}$ A using this code. To obtain the symbolic expressions of $|Y(j\omega)|$, $f(I)$ and $f'(I)$ with MAPLE 9, 0.5 s are necessary.

The APLAC implementation of an A.C. analysis sequence leads to the same frequency characteristics in 6.4 s. This simulation time may be considered as surprisingly long, taking into account that *I* is among the main unknowns of the Harmonic Balance method. The reason behind this long duration is that APLAC doesn't allow the variable I to be included in an user defined model and some iterations are necessary to find the correct value of this variable for each frequency value and for each value of the input voltage.

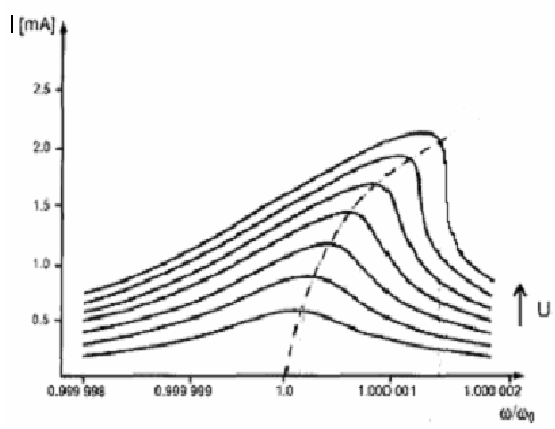

Fig.5. Computed frequency characteristics of a nonlinear quartz resonator

4. DISCUSSION

A symbolic admittance expression has been used to accelerate the analysis of an A.C. parametric model of a power BAW resonator. The parameter being a r.m.s. value, the comparison has been made taking into account a repetitive A.C. analysis performed with APLAC in order to find the parameter value.

The proposed procedure can be used for a filter composed by many resonators. For example, in the

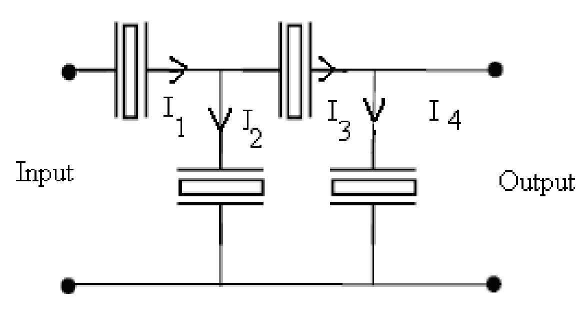

Fig. 6 Ladder filter

ladder filter in Fig. 6 the first resonator, which is the closest to the input source, has the greatest r.m.s. current value and, therefore, its amplitude-frequency effect is the most important. This effect is less significant for the second resonator and so on. In the first step of the analysis the resonators 2, 3, and 4 are supposed to have a linear behavior, so that only the Newton-Raphson iterations with respect to I1 are performed. In the second step the dependences on I2 are considered performing some Newton-Raphson iterations with respect to this variable; after that some Newton-Raphson iterations with respect to I1 are performed taking into account the corrected values R(I2) and R(I2). Because all resonators in the filter have similar geometric and material parameters, usually there is no need to perform Newton-Raphson iterations with respect to all currents.

Because the circuit models of the power BAW resonators exhibiting an “energetic” dependence on the motional branch current can not be implemented efficiently in a circuit analysis program, a method for the fast analysis has been proposed. Using some symbolic expressions, this method has been built taking into account some special properties of the equivalent circuits of the power BAW resonators and therefore can not be used for arbitrary circuits.

Acknowledgement

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