Modeling of Power BAW Resonators

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Abstract: - The circuit models aimed to reproduce both the amplitude-frequency and the intermodulation effects in a power BAW resonator are reviewed. It is shown that the linear parametric models are not able to reproduce the intermodulation effect and cannot be implemented in circuit simulators. Some new nonlinear circuit models are discussed, pointing out that they reproduce both effects and can be implemented in frequency domain and time domain circuit simulators.

Key-Words: - BAW resonators, Circuit models, Nonlinear behavior, Mobile communications.

1 Introduction

The use of the digital radio type solutions in the mobile communications is a challenge in the actual microelectronic technology. Within the next several years the analog RF front end will be integrated together with the digital part 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 [1].

The most robust variant of a BAW resonator, the solidly mounted resonator or SMR, contains, besides the AlN piezoelectric layer and electrodes, some additional layers positioned between the bottom electrode and the substrate (Fig. 1). These last layers

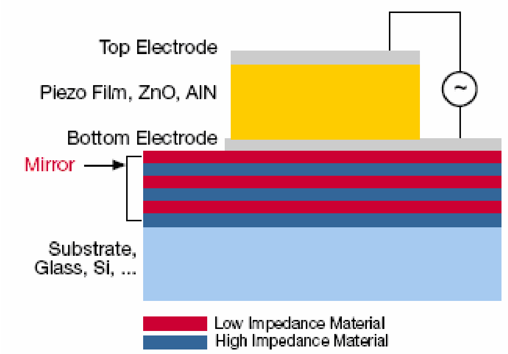

Fig. 1 Solidly mounted resonator (SMR)

form the so-called Bragg mirror, which prevents useless energy dissipation in the substrate.

A valuable tool for the physical design of a competitive resonator or filter is an electromechanical field simulator. The simplest solution is a 1D analytical model, originally stated by Mason, which takes into account only thickness modes [1]. 3D FEM field problem solvers, considering lateral modes also, have been used in the last years for simulations closer to the real world.

As BAW resonators are used to build filters which are parts of intricate circuits, like the power amplifier and duplexer in the mobile phone, circuit models are very useful in the design at system level. This paper is devoted to this kind of models. Section 2 deals with linear models including the parametric circuits developed to reproduce some nonlinear effects. The nonlinear circuit models are discussed in Section 3. Some conclusions and future research directions are presented in Section 4.

2 Linear circuit models

At a relatively low incident power the BAW resonator has a linear behavior which can be described in a broad frequency range by the Mason model [1], a circuit which contains lumped and distributed parameter elements. In the vicinity of a resonance frequency pair (as, for example corresponding to the thickness mode) a simpler model, the Butterworth-Van Dyke (BVD) circuit, can be used (Fig. 2).

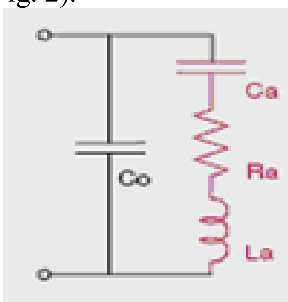

Fig. 2 Butterworth-Van Dyke circuit

A high power fed into the BAW resonator

produces three nonlinear effects, namely: the amplitude-frequency effect, the intermodulation effect, and the bias-frequency effect [3, 4, 5].

The amplitude-frequency effect is illustrated by the series resonance frequency increase as excitation amplitude increases for a quartz resonator (Fig.3) [3]. A decrease of the series resonance frequency as

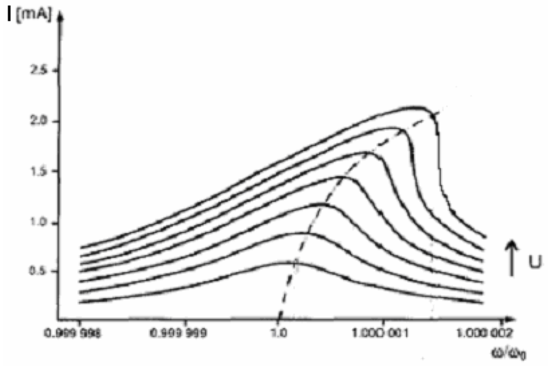

Fig. 3. Frequency characteristics of a quartz resonator (I- resonator current, U- excitation voltage)

the excitation amplitude increases has been observed in the case of an AlN stack crystal filter [5].

The intermodulation effect consists, for example, in measuring some harmonic components of the response to a sinusoidal excitation [3, 4, 5].

The shift of the series resonance frequency as a function of bias voltage is the bias-frequency effect.

The nonlinear behavior of the piezoelectric materials is a 40 years old problem [7]. The most common approach is that a constitutive relation (mechanical, electrical or electro-mechanical) is nonlinear. Some physical models have been proposed on this basis [3, 6] considering the Taylor series development of the nonlinear constitutive equation(s); the coefficients in these developments were called "nonlinear constants". In [7] it is shown that the results obtained by various authors using this type of models do not agree between them. 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. The key reason is that the "nonlinear constants" are computed using some material parameters which can not be measured directly.

…..The linear parametric model in Fig. 4, valid for the response on the fundamental frequency, which is able to reproduce this amplitude-frequency effect is described in [3]. The resistance and the capacitance in the motional branch of the BVD circuit are considered as dependent on the r.m.s. current value I in this branch:

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

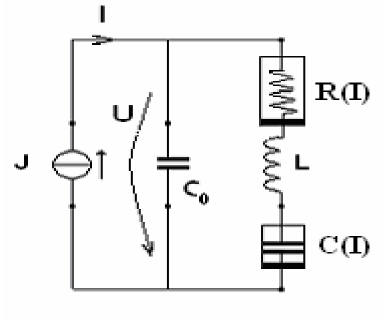

Fig.4. Linear parametric model of a quartz resonator

Being a physical model, the coefficients in the above dependencies are functions of some material constants which are involved in the parameter identification procedure [3]; these constants cannot be measured directly. A similar model for resonators with piezoelectric ceramics is proposed in [6]. A behavioural model with the same structure as that in Fig. 4 is analysed in [8]. The parameter identification procedure of this model is based only on the measured data (the family of frequency characteristics), the approximate formulas for the series and parallel resonance frequencies and the quality factor, the coefficients α and β being estimated using a least squares procedure which uses only measured data. All these linear parametric models can reproduce the amplitude-frequency effect but don't give intermodulation products.

These models contain parametric circuit elements whose characteristics depend on a r.m.s. value. This kind of dependence is not allowed in circuit simulators working in the frequency domain as ADS and APLAC [10]. Moreover, it cannot be used in a circuit simulator working in the time domain as SPICE or SPECTRE [10]. To overcome this difficulty, iterative AC analyses have been implemented in APLAC [8] and MAPLE [9]. Even though these methods can lead to correct results in a reasonable amount of time for the analysis of a circuit composed by several resonators, they cannot be used for the analysis of an intricate system like the power amplifier and duplexer in a mobile phone.

3 Nonlinear circuit models

Starting from an idea in [4] two new nonlinear circuit models have been developed [10]. The first model is based on the BVD circuit in which the nonlinear resistor, inductor and capacitor are implemented as nonlinear controlled sources (Fig. 5). The following parameter values were used for the APLAC implementation of this circuit:

C0 = 1.566e-12
CCVS L1 1 2 1 b [3.5e-9(CI(0)+.1*CI(0)^2+1e-2*CI(0)^3)] L*
CCVS R1 3 5 1 c [430(CI(0)+2e-2*CI(0)^2+2e-2*CI(0)^3)] R*
VCCS C1 3 GND 1 3 GND [.177e-12(CV(0)+5e-5*CV(0)^2+5e-5*CV(0)^3)] C*

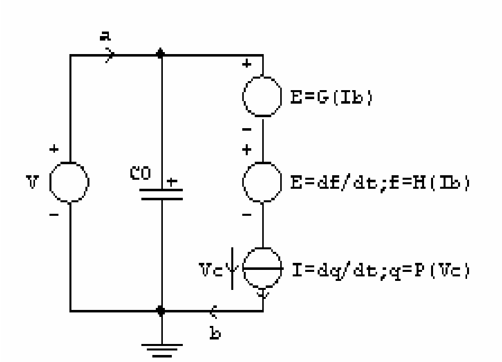

Fig. 5. Controlled source implementation of the first nonlinear circuit model

The amplitude-frequency effect of this model is shown in Fig.6, where the frequency characteristics

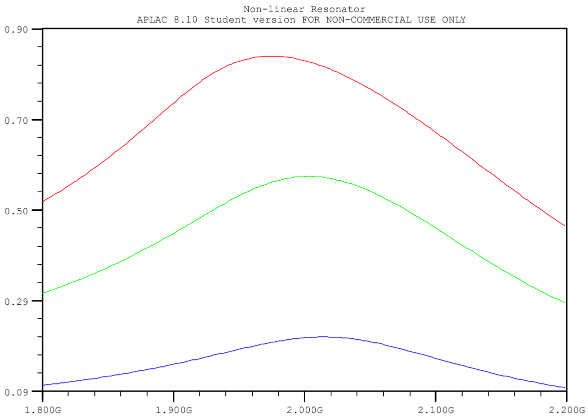

Fig. 6. Ia vs. frequency for the first nonlinear model

for the 1V, 3V, and 5V excitation amplitude are given. The decreasing of the series resonance frequency as the excitation amplitude increases may be observed.

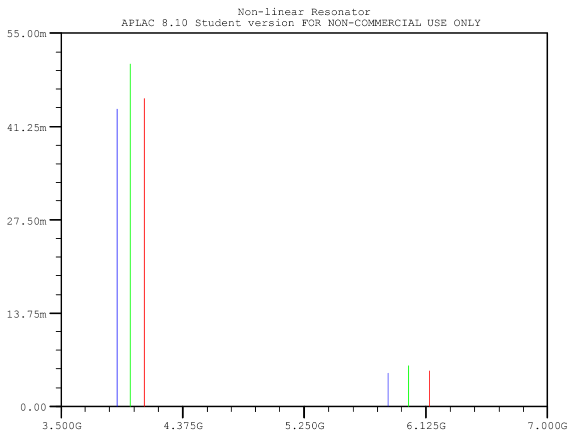

Fig. 7. Intermodulation products for V=5V, first model

The second and third harmonic amplitudes obtained with the first model are given in Fig. 7 for three excitation frequencies.

Forcing the current value in the motional branch by means of the VCCS, the capacitor has a dominant role in this model, both the resonance frequency shift and the amplitudes of the intermodulation products depending mainly on its nonlinear characteristic. To avoid this disadvantage a second model is proposed (Fig. 8). The following parameter

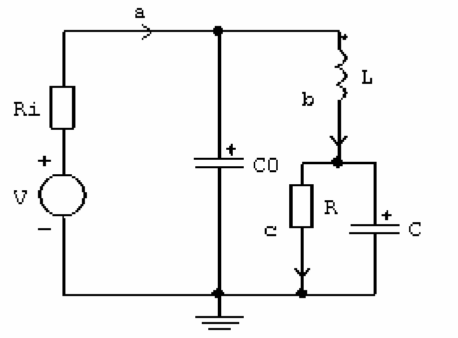

Fig. 8. Second nonlinear circuit model

values were used for the APLAC implementation of this circuit:

C0 = 1.566e-12
CCVS L1 1 2 1 b [3.5e-9(CI(0)+.1*CI(0)^2+1e-2*CI(0)^3)] L*
CCVS R1 3 5 1 c [430(CI(0)+2e-2*CI(0)^2+2e-2*CI(0)^3)] R*
VCCS C1 3 GND 1 3 GND [.177e-12(CV(0)+5e-5*CV(0)^2+5e-5*CV(0)^3)] C*

This circuit shows an amplitude-frequency effect similar to the firs model. Its intermodulation effect is illustrated in Fig. 9.

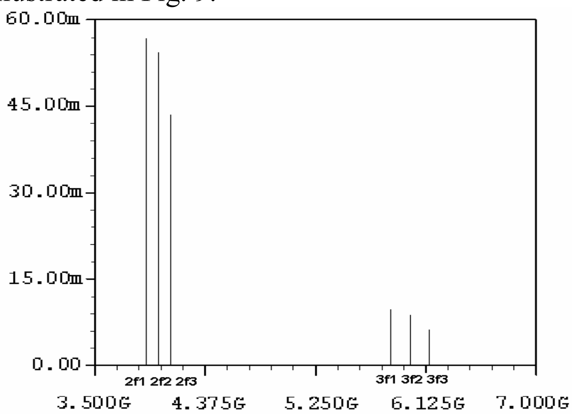

Fig. 9. Intermodulation products for V=5V, second model

In order to show the better fitting properties of this second model, let's modify the inductance parameters as:

CCVS L1 1 2 1 b [3.5e-9(CI(0)+<u>1e-3</u>*CI(0)^2+<u>1e-3</u>*CI(0)^3)] L*

(the changed values are underlined). Using this new inductance the amplitude-frequency effect remains the same, while the amplitude of the second harmonic practically vanishes as it is shown in Fig. 10.

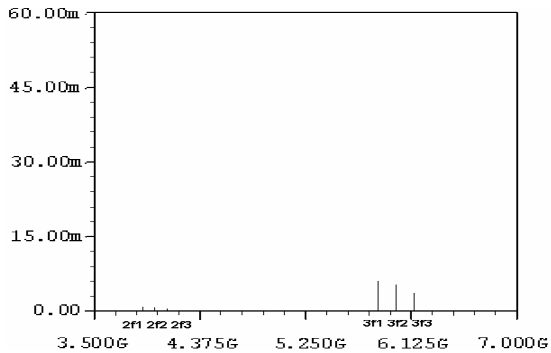

Fig. 10. Intermodulation products for the second model with modified inductor characteristic

The second circuit model allows a better control of both amplitude-frequency effect and intermodulation effect than the first one. This control is obtained by varying the coefficients of the polynomial nonlinearities. If a good enough fitting to the complete experimental data cannot be obtained, new nonlinear circuit models can be developed using simple impedance transformations

These models have been implemented in the APLAC simulator, working in the frequency domain, and in the SPICE simulator, working in the time domain.

…..In order to validate these models, we considered the measured dependence of the series resonance frequency on the incident power [11]. A comparison between the simulated and measured data is given in Fig. 11.

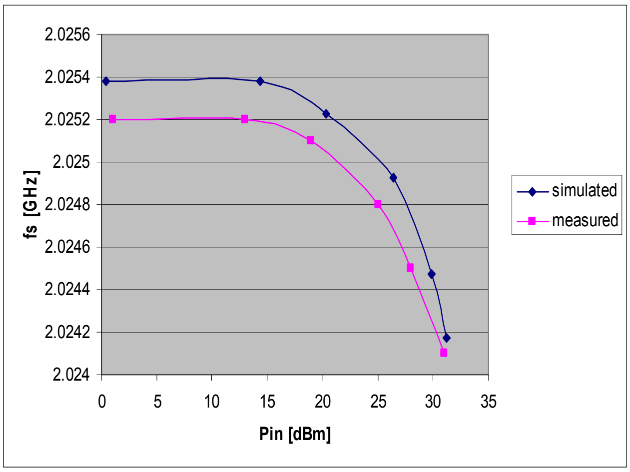

Fig.11. The dependence of the series resonance frequency on the incident power

4 Conclusions

It was shown that linear parametric models don't reproduce the intermodulation effect and cannot be implemented in circuit simulators.

Two new nonlinear circuit models, using polynomial nonlinearities, which reproduce both the amplitude-frequency effect and the intermodulation effect, have been presented. The first model was validated computing the dependence of the series resonance frequency on the incident power, and comparing it with measured data.

Further research will be devoted to parameter identification using real signals from the mobile phone filters.

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