NEW CIRCUIT MODELS OF POWER BAW RESONATORS

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It is proved that known models of power BAW resonators are linear parametric circuits which model only the amplitude-frequency effect. Two new nonlinear circuits modelling both the amplitude-frequency effect and the intermodulation effect are proposed.

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 Bulk Acoustic Wave (BAW) resonators with Aluminium-Nitride (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 BAW technology has been emerging recently as an alternative solution [3].

While at relatively low incident power level a BAW resonator behaves linearly, a high power fed into it produces three nonlinear effects namely: the amplitude-frequency effect, the intermodulation effect and the bias-frequency effect [4, 5]. The amplitude-frequency effect of a quartz resonator implies the increase of the series resonance frequency as the input power increases; the same effect gives a decrease of the series resonance frequency for an AlN resonator as the input power increases [6].

Obviously, a circuit model of a BAW resonator is very useful for the design at the system level as, for example, the duplexer in a mobile phone in which filters are made by several resonators. The linear behaviour of the resonator in the vicinity of the fundamental (thickness) mode is modelled by the well known Butterworth -

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Van Dyke (BVD) circuit. Some linear parametric circuits have been proposed to model the nonlinear effects in power BAW resonators. A critical survey of them is presented in Section 2.

Section 3 contains the description of two new nonlinear equivalent circuits for power BAW resonators. These circuits can model both the amplitude-frequency effect and the intermodulation effect, unlike all other known approaches.

2. LINEAR PARAMETRIC MODELS

The nonlinear behaviour of the piezoelectric materials is an over 40 years old problem [2]. Numerous attempts have been made to explain these phenomena using perturbation theory leading to the identification of the “nonlinear constants” associated to various material properties (elastic, electrical, electro-mechanical coupling).

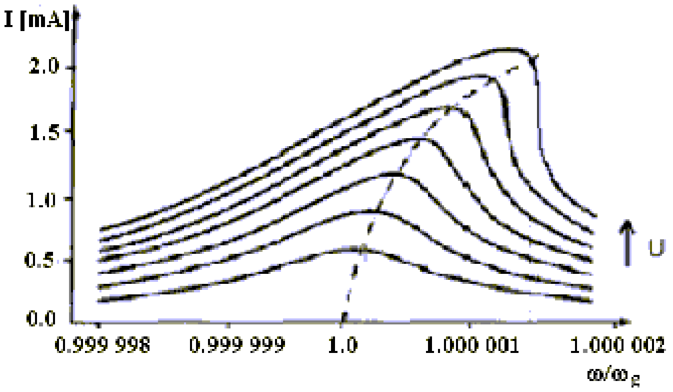

Fig. 1 – Frequency characteristics of a quartz resonator (I- resonator current, U- excitation amplitude)[3].

A linear parametric model (Fig. 2) valid for the response on the fundamental frequency which is able to reproduce this amplitude-frequency effect is described in [4]. 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:

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

The piezoelectric ceramics have an amplitude-frequency effect pointed out by measuring the dependence of the resistance and the reactance in the motional branch of the BVD circuit on frequency and current through this branch [7]. These measurements lead to a linear parametric circuit model similar to that in Fig. 2.

Some results concerning this effect in AlN stacked crystal filters and monolitic filters are given in [6]. A decrease of the series resonance frequency as the excitation amplitude increases is reported in this case. No circuit model is proposed for these filters.

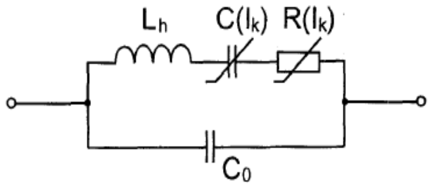

Fig. 2 – Linear parametric model of a quartz resonator [4].

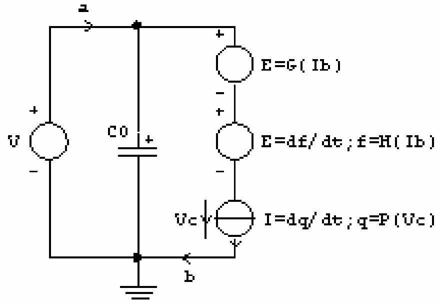

Fig. 3 – Controlled source implementation of the first nonlinear circuit model.

While many papers report intermodulation effect measurements [5, 6, 8], no model which reproduces this effect has been proposed.

The physical models as those described in [4, 7] start from the assumption that at least one of the constitutive equations (electrical, mechanical, electro-mechanical) is nonlinear. In [2] it is shown that the results obtained by various authors using this type of models do not agree between them. The equivalent circuits following from this kind of modelling have the same drawbacks. The key reason is that the so called “nonlinear constants” involved in Taylor series expansions of the nonlinear constitutive equations can not be measured directly. To avoid these difficulties, behavioural models starting from the measured data only have been developed. A parameter identification procedure starting from a given family of frequency characteristics has been proposed in [9] for a linear parametric model similar to that in [4].

The linear parametric models can reproduce the amplitude-frequency effect but don’t give intermodulation products. Simulation of this kind of circuits can be done only using special methods like an iterative AC analysis or a dedicated symbolic method [10]. Nevertheless, these circuit models cannot be implemented in a commercial circuit simulator (working in time domain or in the frequency domain), their utility being only to illustrate the nonlinear phenomena in power BAW resonators in terms of equivalent circuits [10].

3. **NONLINEAR MODELS**

A circuit model of a power BAW resonator having elements with polynomial nonlinearities in the motional branch is suggested in [5] without giving any parameter values or simulation results. Starting from this idea and taking into account the drawbacks of the above mentioned circuit models, the following new nonlinear circuit models have been developed.

The first model is based on the BVD circuit whose schematic is given in Fig. 2. The nonlinear resistor, inductor and capacitor are implemented as nonlinear controlled sources as it is shown in Fig. 3.

The following parameter values were used for the APLAC implementation of this circuit.

```
C0 = 1.566e-12
CCVS R1 1 2 1 b [4.7*(CI(0)+0.5*CI(0)^2+0.5*CI(0)^3)] R
CCVS L1 2 3 1 b [3.5e-9*(CI(0)-5e-2*CI(0)^2+1e-2*CI(0)^3)] L
VCCS C1 3 5 1 3 5 [.177e-12*(CV(0)+1e-2*CV(0)^2+1e-4*CV(0)^3)] C.
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The amplitude-frequency effect of this model is shown in Fig.4, where the frequency characteristics for the 1 V, 3 V, and 5 V excitation amplitude are given.

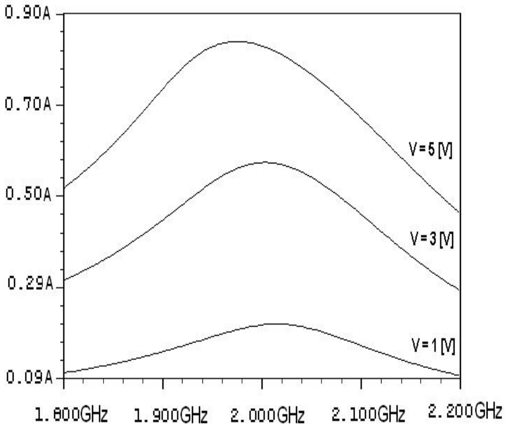

Fig. 4 – Plot of branch “a” current versus frequency for the first model.

The second and third harmonic amplitudes obtained with the first model are given in Fig. 5 and Fig. 6 for three exctation frequencies.

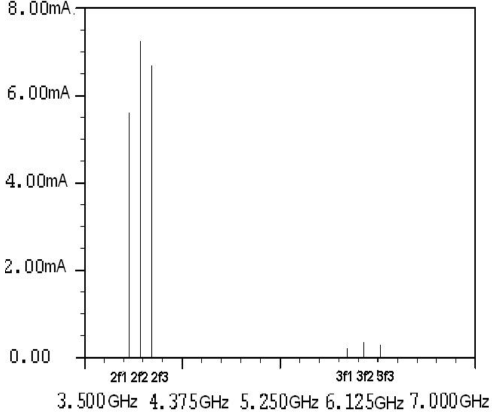

Fig. 5 – Intermodulation products of branch “a” current for $V = 1$V, first model.

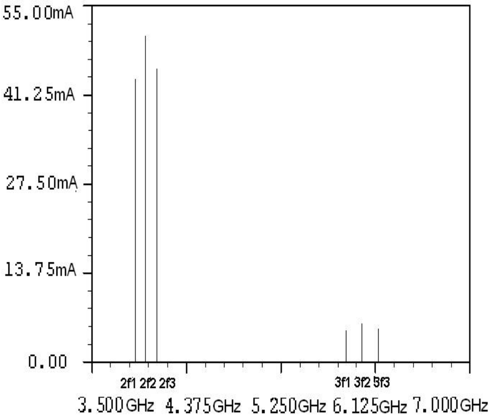

Fig. 6 – Intermodulation products of branch “a” current for $V = 5$V, first model.

Changing the capacitor parameters (underlined values) as

```
VCCS C1 3 5 1 3 5 [.177e-12*(CV(0)+1e-4*CV(0)^2+1e-5*CV(0)^3)] C
```

the resonance frequency shift is diminished (Fig. 7) and all amplitudes of the modulation products are about four times smaller (Fig. 8).

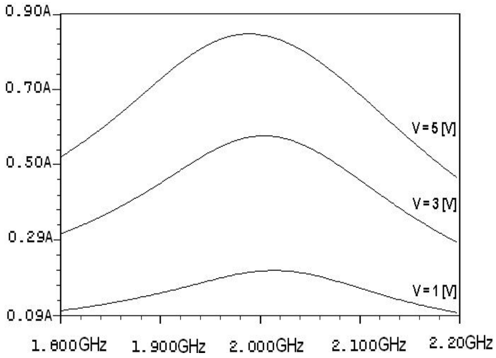

Fig. 7 – Plot of branch “a” current *verssus* frequency for the first model with modified capacitor characteristic.

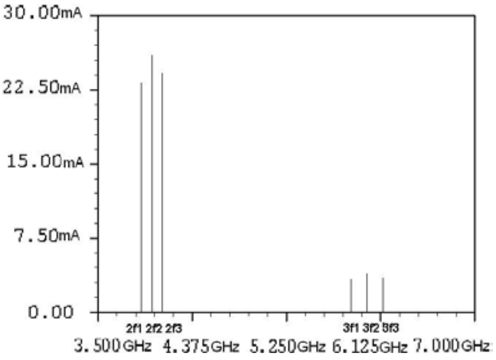

Fig. 8 – Intermodulation products for the first model with modified capacitor characteristic.

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. 9).

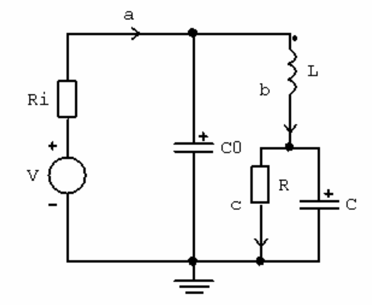

Fig. 9 – Second circuit model.

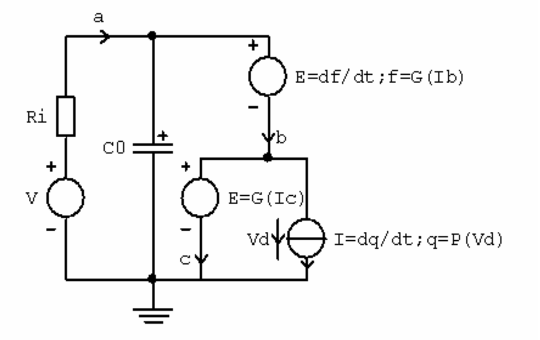

Fig. 10 – Controlled source implementation of the second nonlinear circuit model.

Its controlled source implementation is given in Fig. 10.

The following parameter values were used for the APLAC implementation of this circuit.

```
                  C0 = 1.566e-12
                   Res Ri 4 6 1
  CCVS L1 1 2 1 b [3.5e-9*(CI(0)+1e-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.
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The amplitude–frequency effect of this model is shown in Fig.11 by means of the frequency characteristics corresponding to 1V, 3V, and 5V excitation amplitudes.

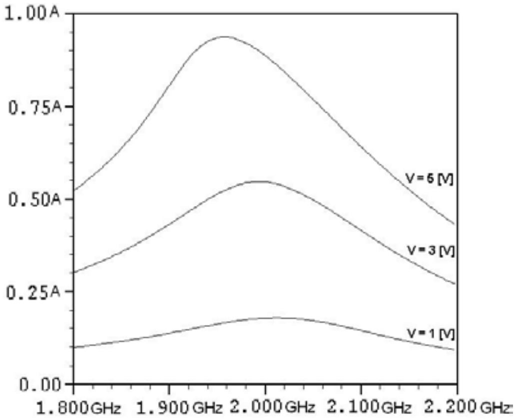

Fig. 11 – Plot of branch “a” current *verssus* frequency for the second model.

The intermodulation products for $V = 5$V are given in Fig.12.

Changing the inductor parameters as

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

the amplitude of the second harmonic practically vanishes (Fig.13).

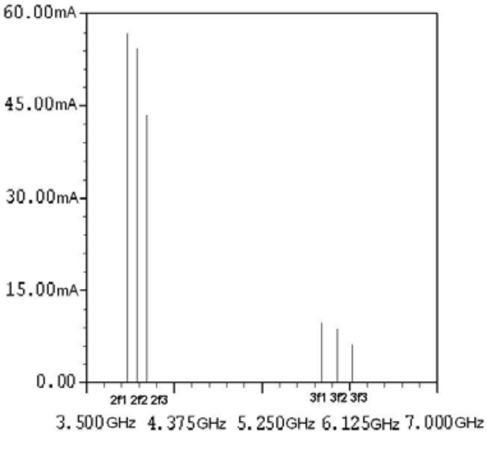

Fig. 12 – Intermodulation products of branch “a” current for $V = 5$V, second model.

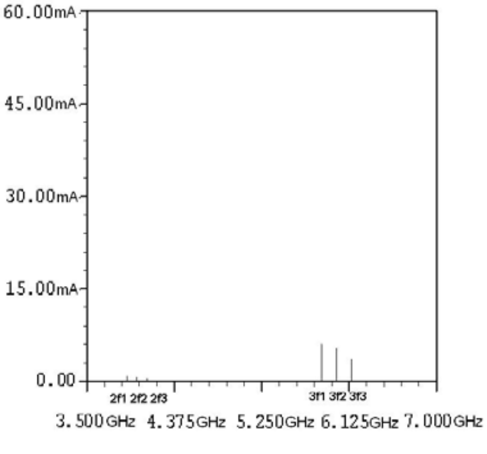

Fig. 13 – Intermodulation products of branch “a” current for the second model with modified inductor characteristic.

4. **CONCLUSIONS**

It has been shown that known models of power BAW resonators are linear parametric circuits which model only the amplitude-frequency effect. Due to the impossibility to measure directly the "nonlinear constants" describing the nonlinear constitutive equations, the behavioural models must be preferred to the physical ones.

Starting from a suggestion in [5], two new circuit models of power BAW resonators have been proposed and analyzed in this paper. These models exhibit both the amplitude-frequency effect and the intermodulation effect, unlike all known models. The APLAC implementation using nonlinear controlled sources was given. Their consistency has been checked, proving that both the amplitude-frequency effect and the intermodulation effect are diminishing as the coefficient values in the nonlinear constitutive equations decrease.

The second model seems to be more flexible than the first one, in order to get a good fit to the measured data. Using some simple relations of impedance equivalence, other models, more suitable for the case in point, can be developed starting from the proposed ones.

Further research will be devoted to the implementation of these models in time domain analysis programs, fit to measured data for filters built up from many resonators using the real mobile phone signals.

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