A Thin-Film BST Varactor Model for Linear and Nonlinear Circuit Simulations for Mobile Communication Systems

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ABSTRACT: A simple model of thin film BST varactors for the use in commercial circuit simulators is presented. The model implies the varactor's nonlinear capacitance as well as the frequency and voltage dependency of the losses. For the use of BST based components in mobile communication systems low tuning voltages are required. This leads unfortunately to high nonlinear distortion which is not acceptable. Another severe problem are the moderate to low quality factors and therefore high losses of the ferroelectric capacitors. The presented model allows estimating the losses and the distortion over a wide frequency range at every bias state with harmonic balance and envelope simulations. Further more it is now possible to predict the behavior of a designed circuit but also to deduce the requirements for BST varactors in order to achieve the demanded design goals. The model consists of a parallel circuit of equation based elements which represents the nonlinear capacitance and conductance. A constant series inductance and a constant resistance model the contacts. The required parameters can easily be extracted through measurements. To demonstrate the validity of the presented model a BST based SP2T switch at 1800 MHz was designed. An insertion loss of 1.4 dB at an isolation of 21 dB and a TOI of 35 dBm were achieved. The simulation and measurement results agree very good over a wide frequency range.

Key words: BST, varactors, model, nonlinear, electrostriction

1. INTRODUCTION

Today's mobile communication devices like mobile phones and wireless LAN cards have to support more and more communication standards at different frequency bands. To make those multiband and multistandard radios affordable considerable efforts were made on semiconductor integration. Unfortunately the semiconductor technology has its limits in terms of realizing tunable RF frontend components. Alternative candidates are ferroelectric based components like barium strontium titanate (BST) varactors.

To analyze the possibilities and the application areas a capacitor model for a common circuit simulator is needed which allows investigations on system level. This model should permit small signal as well as large signal simulations over a wide frequency range.

In this paper we will present the different components of a BST capacitor model and the implementation with nonlinear equation based devices. These nonlinear devices should allow the description of the port currents in terms of the port voltages. Furthermore it must be possible to calculate the time derivative of a port voltage.

For the shown simulation results the symbolically defined device (SDD) elements of the Agilent ADS® circuit simulator were used [5]. But the presented model could also be implemented in any other circuit simulator who supports the described nonlinear equation based devices. To show the validity and the limits of the model we present also measurement results of a BST based SP2T switch.

2. VARACTOR MODEL

Fig. 1 shows the elements of the implemented BST varactor model. In the following we will discuss consecutively every element and the implementation in the circuit simulator.

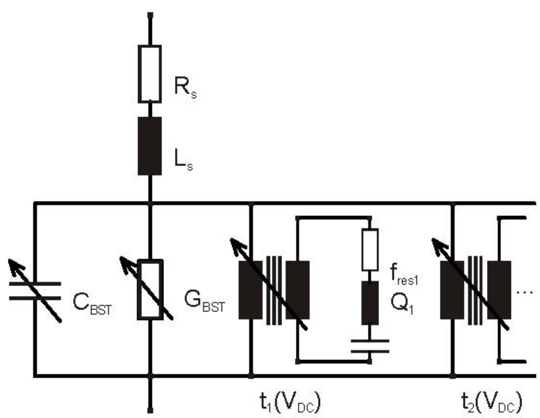

Fig. 1: Components of the BST varactor model.

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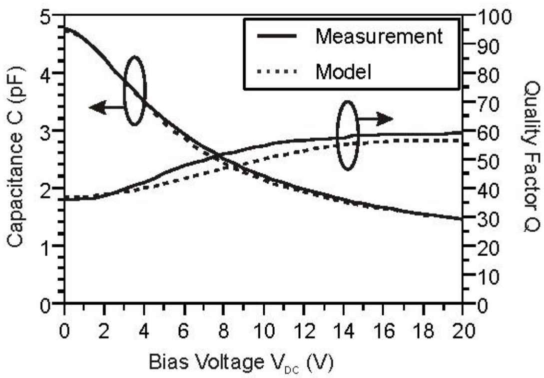

Fig. 2: Comparison of measured and modeled C(V) and Q(V) relation at 800 MHz.

2.1 Electrode effects

To account for the effects of the electrodes the model includes a series resistance R_s and inductance L_s. As we see later we need a thin top electrode to shift electrostrictive resonances to high frequencies. This electrode can contribute significantly to the overall loss of the capacitor at higher frequencies and must therefore be considered. Fortunately this effect is linear and can be characterized by a simple resistor. The series inductance that limits the usable frequency range of the capacitor is also linear. The values of both elements could be calculated with the use of an EM simulator or can be extracted from measurements of test structures.

2.2 Nonlinear capacitance

As derived in [1] the nonlinear capacitance can be described by the following expression:

$$C_{BST}(v) = \frac{C_0 - C_f}{2\cosh\left(\frac{2}{3}\operatorname{arsinh}\left(\frac{2V}{V_{1/2}}\right)\right) - 1} + C_f . \qquad (1)$$

Where C_0 is the capacitance at V=0 V less the fringing capacitance C_f. $V_{1/2}$ is the voltage where $C(V_{1/2}) = C_0/2$.

To implement this characteristic we need a two port SDD. The ADS SDDs allow two different ways to describe port voltages and currents. One possibility is to define the port currents I_i directly as a function of the port voltages V_i

$$I_i = f(V_i) \qquad (2)$$

The second possibility is to use an implicit equation

$$f(I_i, V_i) = 0 \qquad (3)$$

In our case we use a direct equation at port 1

$$I_1 = C(V_1)V_2 \qquad (4)$$

and an implicit equation at port 2 to calculate the time derivative dV_1/dt of the voltage V_1 at port 1

$$\frac{d}{dt}V_1 - V_2 = 0 . \qquad (5)$$

It should be noted that V_2 is only used as an auxiliary variable. Fig. 2 shows a comparison of the modeled and measured C(V) relation of a 5 pF capacitor. The parameters can easily be obtained by the use of a curve fitting tool like the Matlab® function *lsqcurvfit*.

2.3 Nonlinear conductance

In the mobile communications relevant frequency area, above 800 MHz, the series resistance of the electrodes dominates the losses. Nevertheless measurements revealed that the effect of the nonlinear parallel conductance G_{BST} is not negligible [2]. The dielectric loss originates from many different phenomena [3]. To simplify the model we assumed the dependency of the conductance on the applied voltage as follows:

$$I = \gamma_0 V + \gamma_1 \arctan\left(\frac{V}{\gamma_2}\right) \qquad (6)$$

The differential conductance is then

$$G_{BST}(V) = \gamma_0 + \frac{\gamma_1/\gamma_2}{1 + \left(\frac{V}{\gamma_2}\right)^2} \qquad (7)$$

where γ_0, γ_1 and γ_2 are fitting parameters which could be determined at a single frequency point in the same way as mentioned above. Depending on the frequency range you are looking at, the resulting quality factor could be modeled very closely. Nevertheless there are some accuracy limitations when modeling a wide frequency range like in tunable filter applications. Fig. 3 shows a comparison of measurement and model in a frequency range from 0.5 GHz to 3 GHz. The same results are plotted in Fig. 2 in dependency of the applied bias voltage at 800 MHz. Obviously there are some deviations from the measurements which could be avoided if the model would be optimized only for 800 MHz.

2.4 Electrostrictive Effects

Electrostrictive resonances are one of the most troublesome effects in thin film varactors. The thickness of the top electrode and the resulting mass determines the resonance frequency which could occur in the operating frequency band. Fig. 3 shows a capacitor with acoustic resonances at the multiples of 1.5 GHz. Depending on the design of the electrodes and the properties of the substrate more than one acoustic mode is stimulated at slightly different resonance frequencies and the resonance notch broadens.

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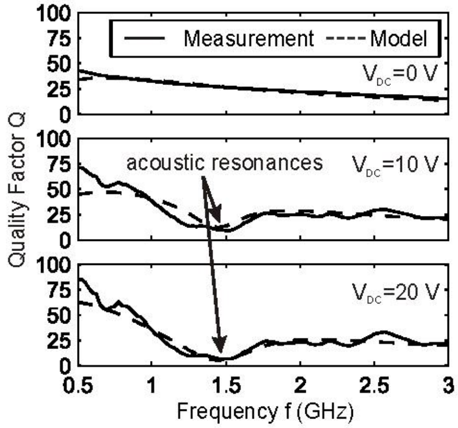

Fig. 3: Quality factor over bias voltage and frequency.

The perovskite-type BST crystal which is operated in its paraelectric phase has, in absence of an electrical field, a centrosymetric structure and therefore shows no piezoelectric effect [4]. With increasing bias field the crystal becomes asymmetric and a piezoelectric resonance can be observed as illustrated in Fig 3.

Measurements showed that the coupling could be modeled with a linear dependency from the bias voltage. To model this effect we used a three port SDD. For an easy description the transformer with a series resonator is converted to a gyrator with a parallel resonator. The third port of the device is connected with a low pass filter to obtain the bias voltage $V_3=V_{DC}$. The relations are

$$I_1 = \sqrt{k|V_3|}V_2 \tag{8}$$

$$I_2 = -\sqrt{k|V_3|}V_1 \tag{9}$$

$$I_3 = 0 \tag{10}$$

(8) and (9) are the relations for the gyrator. The admittance Y_G at the input of the gyrator is then

$$Y_G = kV_3Z_P \tag{11}$$

where Z_P is the impedance of the parallel resonator circuit. At zero bias voltage the input admittance is zero and not recognized by the varactor. With increasing bias voltage admittance increases too and inserts the emerging acoustic resonance.

3. SP2T SWITCH

To show the validity of the capacitor model we built a SP2T switch depicted in Fig. 4 based on four tunable resonators. Each resonator consists of an inductor L_{res} and two BST varactors. To lower the tuning voltage and to enhance the linearity the capacitors are shunted for DC and cascaded for RF. With V_1=0 V and V_2=15 V the resonators in the branch of port 2 are in resonance which means that the parallel resonator behaves like an "open" and the following series resonator behaves like a "short". So this branch is switched off. At the second branch the applied bias voltage ensures that the resonators are not in resonance and therefore this branch is switched on. Matching networks help to improve the match at the connected ports.

3.1 Linear behavior

The initial design was optimized to work in the GSM 1800/1900 frequency band. Unfortunately the capacitance of the manufactured varactors was a bit smaller than expected and the operating frequency range shifted to higher frequencies. As depicted in Fig. 5 the simulation was repeated with the actual capacitance values. The measured minimum insertion loss of 1.4 dB and isolation of 21 dB were slightly worse than expected due to component deviation.

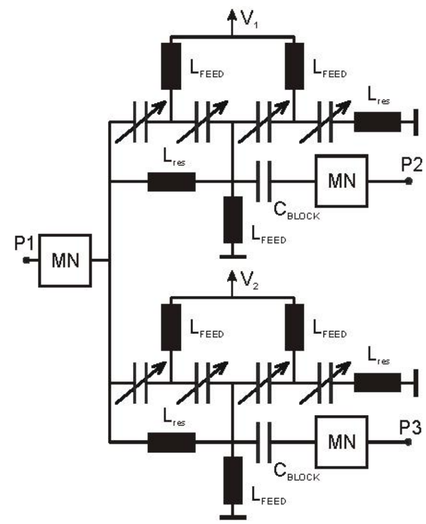

Fig. 4: Schematic of the realized SP2T switch.

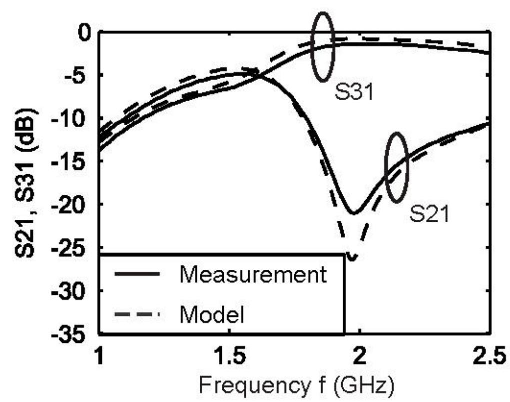

Fig. 5: Measurement and simulation results for transmission and isolation.

3.2 Nonlinear behavior

To characterize the nonlinear behavior we used a two tone measurement setup. Fig. 6 shows measurement and simulation results for transmission P_{out}, isolation P_{iso} and generated intermodulation products P_{IM3}.

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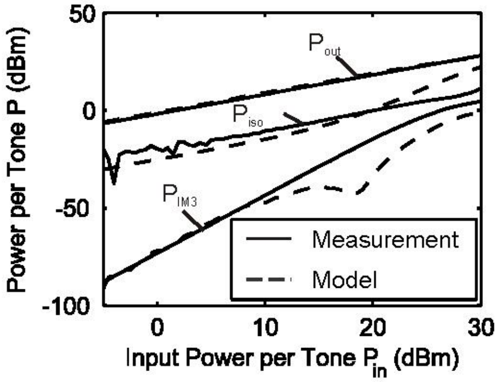

Fig. 6: Measurement and simulation results for two tone measurements.

Up to an input power of 10 dBm the simulation agree pretty well with the measurement results. Above 10 dBm 5th order products arise and a cancellation of 5th and 3rd order intermodulation products could be observed. Another interesting result is that the isolation declines 10 dB later than predicted. From these measurements a TOI of 35 dBm was calculated.

4. MEASUREMENTS

To determine the properties of the BST capacitors we used a R&S ZVB8 network analyzer as well as an Agilent 4991A RF impedance analyzer with SOL calibration.

Our measurements showed that quality factors above 60 are very difficult to measure with a network analyzer. Due to the different system configuration the impedance analyzer is more appropriate for this purpose [6]. On the other hand today's impedance analyzers are limited to a maximum frequency of 3 GHz.

For an extensive characterization of the varactors we used both instruments. For the measurement of the self resonance frequency and the resulting series inductance we used the network analyzer. To model the dielectric loss and capacitance we used the impedance analyzer.

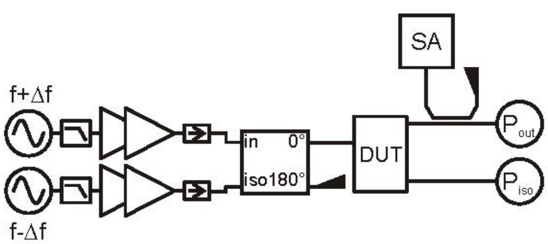

Fig. 7: Two tone measurement setup for the nonlinear characterization.

To measure the nonlinear properties a two tone setup depicted in Fig. 7 was used. The TOI of the measurement setup was more than 50 dBm. With a two channel power meter we measured the transmitted and isolated power at port 2 and 3. A spectrum analyzer was used to measure the intermodulation distance.

5. DISCUSSION

The measurement results demonstrated that it is very difficult to characterize BST varactors with high precision. Non ideal calibration standards and the inaccuracy of the measurement instruments limit the precision of the results.

Additionally superimposed effects like electrosrictive resonances and the nonlinear parallel conductance make a distinction between these effects very difficult. With the use of curve fitting tools only an approximation over a wide frequency range can be determined.

The nonlinear measurements showed that the in [1] assumed power-series expansion of the field polarization up to the 3rd order is only practicable to a certain power level. At higher power levels higher order terms must be considered.

6. CONCLUSION

We have demonstrated how to implement a capacitor model for the use with linear and nonlinear circuit simulators. To validate the model and to show the limitations we built a varactor based SP2T switch with 1.4 dB insertion loss and 21 dB isolation at a TOI of 35 dBm. Whereas the simulation and measurement results showed a good agreement at lower power levels the results diverged at higher power levels.

However the proposed model could be used for the design of wideband applications like tunable filters and to estimate the nonlinear behavior. It can help to deduce the requirements for the varactors in order to fulfill certain design goals like TOI or insertion loss.

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