Characterization and Modeling of Continuously Tunable MEMS Varactor

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***Abstract*—In this work a circuit model for a continuously tunable varactor is presented which is based on a microelectromechanical system (MEMS). This behavioral model can be implemented in commercially available simulation tools and allows for complete circuit simulations in terms of small- and large- signal performance, as well as for transient and envelope responses. For the present implementation Agilent's ADS is used but the modeling methodology can be generalized for use in other tools as well. For the MEMS varactor which is investigated in this paper good agreement is obtained between simulated and measured data. The capacitance variation for different tuning voltages as well as the frequency and power dependency of the component are discussed. For a bias voltage range up to 130 V a capacitance tuning ratio of more than 5:1 is obtained. The excellent linearity provided by minimal self actuation effects qualify the component for use in high power applications.**

I. Introduction

Over the last years the demand for tunable passive devices which allow for reconfigurable microwave systems has raised significantly. Tunability in microwave systems has become an issue since the complexity of radio communication devices has increased dramatically. Transceiver architectures, in both hand held devices and base stations, face an increasing number of communication standards which have to be covered. The expanding wide frequency allocation of those standards and the worldwide varying regulations impose tight specifications since overall system efficiency and power consumption have to be optimized simultaneously. Tunable passive devices based on ferroelectric [1], [2] or MEMS components [3] have already proven their potential for use in reconfigurable systems, since they allow for implementations of tunable and frequency agile subsystems. So far, the properties of those components have been investigated mostly by academic research groups. Nevertheless, over the last years activities have been reinforced also by industrial parties [4]. Designing high performance circuits based on tunable components is a challenging task and is influenced by the structure of the component, the RF-performance, and also its assembly within the circuit. Therefore all of these aspects are discussed in the following sections. The used MEMS varactor and its properties are discussed in section II. The behavioral model and its implementation in a circuit simulator tool are presented in section III. Finally, the comparison between simulated and measured component performance is given in section IV.

II. Cantilever MEMS Varactor

For the characterization and modeling activities a micromechanical varactor from Siemens Corporate Technology in Munich was used. It comprises of a piezoelectrically actuated cantilever structure as shown in Fig. 1. Construction details are presented in [5]. The whole layer stack is based on a ceramic substrate (LTCC) and through vias a conductive path is provided to the backside of the LTCC substrate.

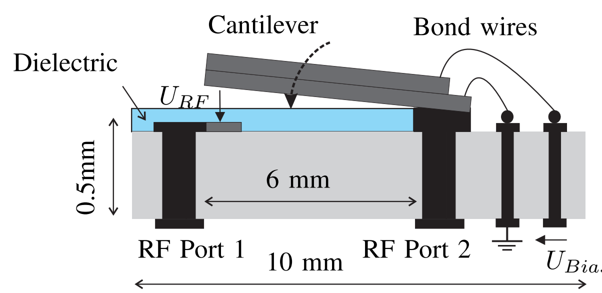

Fig. 1. Schematic of a cantilever MEMS varactor.

The top electrode includes lead-zirconate-titanate (PZT) material and forms a cantilever which bends down due to piezoelectric activation. The tuning voltage U_{Bias} can be varied between 0 and 200 V corresponding to an air gap in the range of 20 and 2 μm between the top and bottom RF electrodes, who are directly attached to the two RF ports. That means increasing the tuning voltage leads to larger bending and thus smaller gap resulting in increased capacitance. By that a continuously tunable varactor is obtained. Besides this wanted piezo actuation there is a secondary unwanted electrostatic actuation caused by an electrostatic force between the two RF electrodes [5] forming the capacitance. By applying large RF voltage a parasitic electrostatic force pulling down the cantilever is found. As this force is proportional to U_{RF}^2 it is always pulling down. This mechanism of self actuation by the carried RF signal is the main cause for nonlinearities in the RF-path of the varactor. But electrostatic forces tend to be much smaller than piezoelectric forces leading to very minor bending of the cantilever. The cantilever can also be treated as a mechanically oscillating system associated with a moving mass, a spring constant, and damping by the air in the gap. From analysis of the mechanical dynamic properties a mechanical resonance frequency around a few kHz is found. For any wideband modulated signal that has larger bandwidth than the mechanical resonance, e.g. UMTS with 5 MHz channels, the nonlinear distortions due to self actuation are very low. The inertia of the mechanical system is too high to follow the fast envelope fluctuations. The highest capacitance is observed when the cantilever is most down and facing the dielectric layer that is capping the lower RF electrode. A parallel plate capacitor with distance d_k equal to the thickness of the dielectric capping layer, ε_k of the capping layer, and area A equal to the electrode size of $1\,mm^2$ is formed. The capacitance can be expressed as $C = \varepsilon_k \cdot \varepsilon_0 \cdot A/d_k$.

Due to separation of the RF signal and the Bias path it is possible to use the varactor in series configurations without additional circuitry such as bias-Ts. This is a nice feature since this type of components would contribute to a degradation of the RF circuit performance.

III. Behavioral Model for Circuit Simulations

Designing high performance microwave circuits is impractical without having appropriate models which can be used in commercially available design tools. In this work, we use Agilent's Advanced Design System (ADS) for implementing an equivalent circuit model, as in [6]. The core element of the proposed model is the symbolically defined device (SDD) as it is available in the ADS library. These SDD objects are powerful elements since they allow for implementation of equation based, user defined, nonlinear, and frequency dependent components. They can be used as multi port elements and describe the relationship between port voltages and associated currents, and their time derivatives along with currents from other devices. For a SDD device with n-ports, the current i at any port can be described in dependence of all other port voltages u, as

$$i = f(u_1, u_2, ..., u_n) \tag{1}$$

where f is a user defined function. In case of the investigated MEMS varactor the overall capacitance is described as

$$C = \frac{\varepsilon_0 A}{\frac{d_k}{\varepsilon_k} + g + z}. \tag{2}$$

In (2), the denominator includes all parameters which determine the cantilever movement and thus the distance between the two capacitor electrodes. The air gap g is directly proportional to the applied bias voltage U_{Bias} and can be described by the following relation

$$g = g_{max} - (U_{Bias} + aU_{RF})b. \tag{3}$$

The constant a accounts for the crosstalk between the RF and DC path, while b is a constant determined by the cantilever geometry. The parameter z stands for the vertical movement of the cantilever tip and is related to the mechanical properties of the cantilever electrode. Considering the cantilever motion as a system with a single degree of freedom, allows for a simple representation with a differential equation of the following form

$$M\ddot{z} + D\dot{z} + Kz = F(t). \tag{4}$$

In (4), M is the moved top electrode mass, D is the damping constant, K the stiffness parameter, and $F(t)$ the time variant actuating force. In this case, F is the electrostatic force. For a parallel plate capacitor with applied RF voltage U_{RF}, the electrostatic force is given as

$$F(t) = \frac{\varepsilon_0 A U_{RF}^2}{(d_k/\varepsilon_k + g)^2}. \tag{5}$$

Combining (2), (3) and (5) yields to the expected relation between bias voltage, cantilever movement, and the resulting capacitance variation.

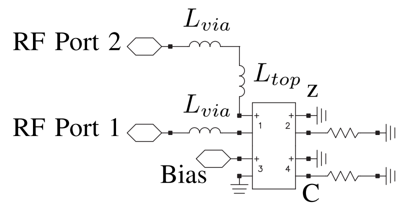

Fig. 2. Implemented MEMS varactor model using an ADS SDD element.

The implemented model using an ADS SDD element is depicted in Fig. 2. Both RF ports are connected through inductive elements to connector pair 1 of the SDD. The lumped inductances account for the top electrode and the vias connections. The formed air gap and its relation to the applied bias voltage and RF signal according to (3) is formed at connector pair 3. Connector pair 2 of the SDD element is used for describing the cantilever movement parameter z, according to (4) and (5). Finally, at connector pair 4 of the SDD the overall parallel plate capacitance is described as in (2), taking into account all the aforementioned effects.

IV. Measurement Results

A. Small Signal Performance

The MEMS component was characterized by scattering parameter measurements which were taken with a vector network analyzer (VNA), as in Fig. 3 where the reference plane is indicated by dotted lines. The capacitance of the varactor was calculated from the measured reactance, according to the relation

$$C = \frac{\Im\{Y_{21}\}}{2\pi f} \tag{6}$$

where Y_{21} is the admittance of the transmission path. A comparison of measured and simulated data for different bias voltages is presented in Fig. 4.

A large tuning ratio of more than 5:1 reveals the potential of using this element in tunable microwave circuits. The measured and simulated transmission scattering parameters S_{21} are depicted in Fig. 5. The good agreement qualifies the model for use in circuit simulations for designing microwave circuits with tunable or reconfigurable characteristics.

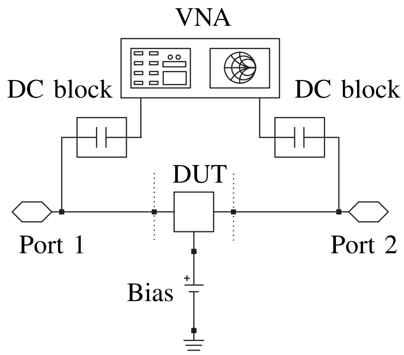

Fig. 3. Measurement setup for component characterization.

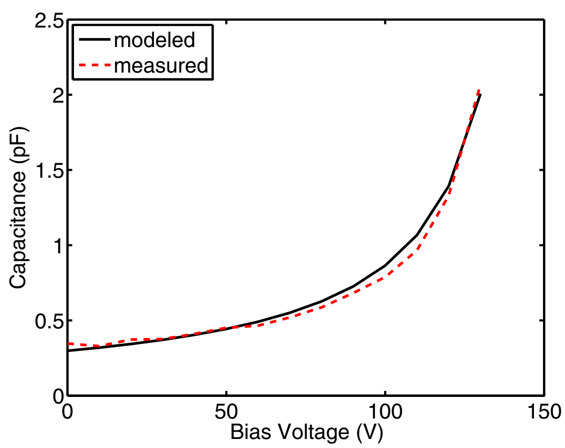

Fig. 4. Measured and modeled capacitance of MEMS varactor.

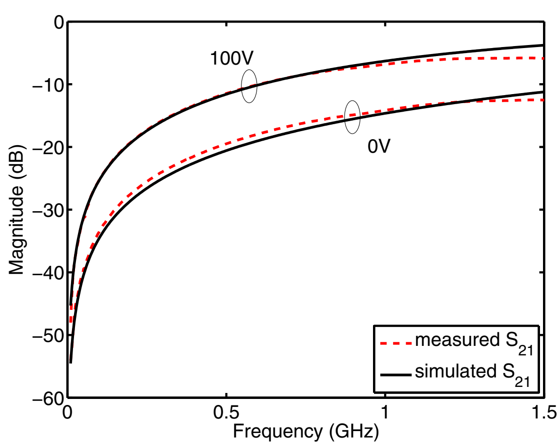

Fig. 5. Measured and modeled transmission scattering parameter S_{21} of the MEMS varactor for different bias voltages.

B. Linearity Performance

Besides the capacitance variation and the frequency dependence, the varactor has to be characterized for its power handling capabilities. As can be seen in Fig. 6, the varactor performance can be described by the proposed model thus allowing for complete system investigations in circuit simulation tools at an early design stage. As it is readily seen from Fig. 4, the MEMS varactor is tunable thus inherently nonlinear. The nonlinear performance of the element has to be investigated since it is aimed for use in microwave communication systems. A typical two tone setup used for such investigations is depicted in Fig. 7. A comparison between output power and corresponding intermodulation product power levels can be used for estimating the nonlinear effects of the MEMS element. Two RF-signal sources are used to produce the sinusoidal tones with individual frequencies f_1 and f_2. The attenuation between the power amplifier modules and the DUT is corrected thus the absolute power level P_{in} is presented at the input port of the DUT. The output port is connected through a coupler to a power meter (PM) and a spectrum analyzer (SA) to capture the corrected output power and the intermodulation product levels, respectively.

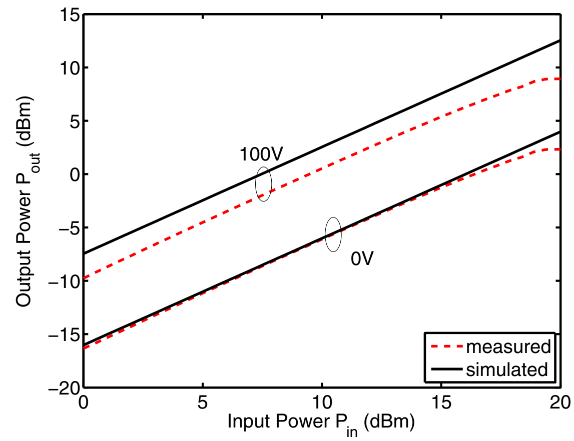

Fig. 6. Measured and modeled power handling of MEMS varactor at tone frequency of 850 MHz.

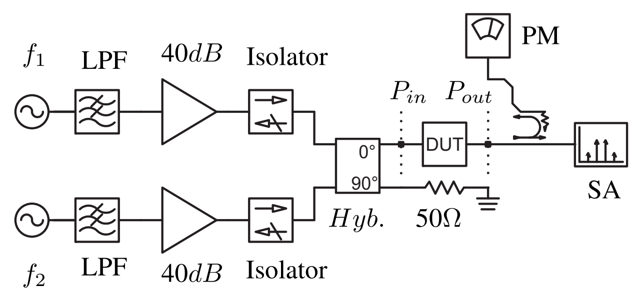

Fig. 7. Schematic of two tone measurement setup.

The MEMS varactor implies a mechanical movement of the piezoelectric cantilever as described in (4). The electrostatic force F is ruled by the applied RF signal and its frequency thus the cantilever movement will be also frequency dependent. This relationship is investigated by the simulated data in Fig. 8. Varying the tone distance results in different intermodulation product power levels. For both simulated bias states there is a peak at 2.2 kHz where the cantilever movement is resonant. For use in communication systems this condition should be

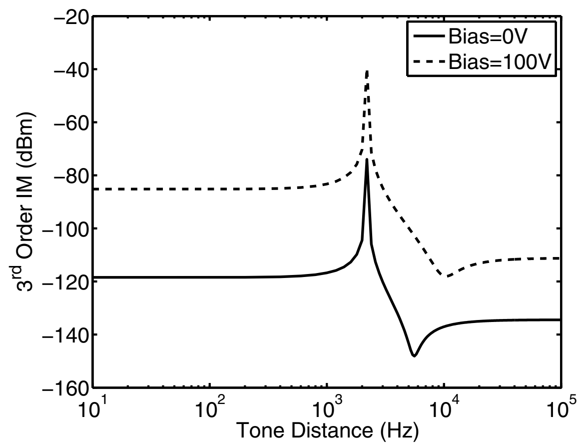

Fig. 8. Simulated 3^{rd} order intermodulation product (IM) for varying tone distances. A tone power of P_{in}=20 dBm is assumed and the responses for two discrete bias states are displayed.

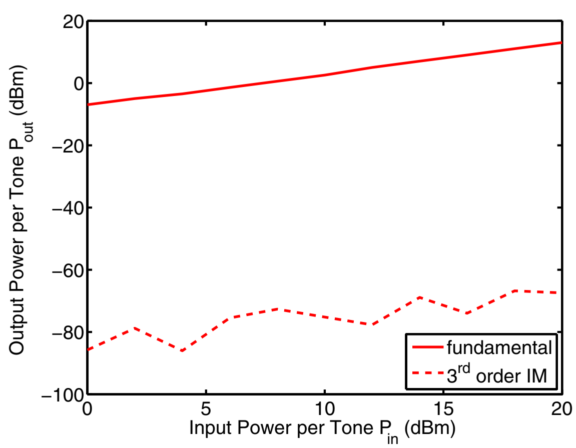

Fig. 9. Measured output power levels of the fundamental tone and intermodulation products at bias voltage 100 V.

rarely met, since the corresponding channel bandwidths are much wider.

In the used measurement setup the two tones were allocated around the center frequency of 835 MHz with a tone distance of 5 MHz. The measured response with the described setup is depicted in Fig. 9. It is noteworthy that the measured power levels of the 3^{rd}-order intermodulation products are very low at all bias states. As a result, they hardly exceed the noise level of the described measurement setup thus they can not be traced properly over the entire sweep range. The resulting intermodulation products are at least 70 dB lower than the fundamental tone over the whole power sweep range. It is evident that this cantilever MEMS varactor is very well suited even for high power microwave circuits since it exhibits excellent linearity.

Compared to ferroelectric varactors, the investigated MEMS element has a much higher tuning range while exhibiting even better linearity [7]. At the same time, the high tuning voltages and the overall large component dimensions have to be considered as drawbacks compared to other technologies, namely ferroelectric components which have a much higher potential for integration in mobile devices. Nevertheless, the overall performance in terms of capacitance tuning ratio and linearity qualify this type of MEMS varactor for designing reconfigurable microwave circuits with enhanced linearity specifications.

V. Conclusion

In this work the characterization and the behavioral modeling of a cantilever MEMS varactor is discussed. As a result, a circuit model is presented which can be implemented in commercially available simulator tools. In this case, we used Agilent's ADS circuit simulator. The implemented circuit model allows for simulations of small- and large signal behavior and its suitability was demonstrated by comparison of measured and simulated performance of a cantilever MEMS varactor. Good agreement is obtained over the investigated frequency region. The obtained tuning ratio of more than 5:1 is achieved at a bias voltage range of 0-130 V. The linearity performance of the MEMS element was investigated by a two tone measurement setup. The varactor exhibits excellent linearity at all bias conditions and is clearly suited for designing tunable or reconfigurable microwave circuits with tight linearity requirements. Large component dimensions along with high bias voltages of up to 130 V remain as a drawback compared to other tunable devices. Although the utilization in hand held devices appears to be impractical the MEMS varactor is still an attractive solution for stationary devices with high power applications and increased linearity requirements.

Acknowledgment

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