Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

DESIGN OF CRYSTAL OSCILLATORS BY USING SIMULATORS

S. E: Overhoff[1], D. Hildenhagen[2], K. Solbach[2]
[1]Siemens AG, ICM MP, Kamp-Lintfort, Germany
[2]Gerhardt-Mercator-Universität, Duisburg, Germany

Abstract - **The design of crystal oscillators in cell phone applications intended for high volume production is a challenge. In the past, the development was based on empirical formulas and the designer's experience. During development a good prediction of the oscillator performance is desired. This resulted in a trial and error process. A deficiency of this method is that a lot of impacts could not be studied easily. Today, it is additionally possible to use modern design tools to ensure a so-called "robust design". To enhance the accuracy precise models of various circuit parts have to be available. In this paper models for the circuit components in use and the layout influences will be presented. Also, models for the used resistors and the varactor diode will be described. The models for the resistors and the layout influence will be derived from measured data. The main focus of this paper will be the behaviour model of the varactor diode under large signal conditions: Since, in the crystal oscillator in use, the varactor works under large signal conditions, the simulation has to include capacitance variation due to high RF voltage swing. However, in commonly available SPICE-models only a description of the small signal behaviour is obtained and no large signal model is available.**
***Keywords -* Capacitance diode, Crystal oscillator, Simulation, Modeling**

I. INTRODUCTION

In the past the design of crystal oscillators was mostly based on empirical formulas and the designer's experience. The development was done with a trial and error process. Deducing the behavior of the oscillator from previous designs often complemented this. A lack of this method is that a lot of impacts could not be studied easily. The impact of component variations on the oscillator behavior could only be studied by using components with extreme values. A lot of measurements had also to be carried out to characterize the performance of the oscillator. Today, it is additionally possible to use modern design tools like circuit simulators. Building up a crystal oscillator in a circuit simulator is a challenge. In order to achieve a good match between simulation results and measurement data good models of the circuit components have to exist. To simulate the initial frequency of a crystal oscillator with normally used models for the circuit components will end up in differences of several hundred ppms between simulation data and measurement. A good match between simulation and measurement is achieved, if the difference is smaller than the specified initial frequency tolerance of the oscillator

II. COMPONENT MODELLING

First of all, for every component the operating conditions in a crystal oscillator have to specified and measured. The resistors and capacitors are investigated to verify their impedance locus diagram versus frequency. Different parameters were also identified to have an impact on the capacitance diode resistance locus diagram. These parameters were the applied DC voltage, the AC voltage swing across the diode and the ambient temperature. For the crystal the following parameters were determined to have some impact. First of all the ambient temperature and secondly the crystal drive level. For the transistor, the following parameters were identified: The DC operating point, the AC voltage swing and the ambient temperature.
First of all, the resistors and the capacitance diode were investigated and modeled.

A. Resistor Model

For mass production typically leadless components are used. These components are called "Surface Mount Devices". First of all, measurement data of different resistors, used in the crystal oscillator, were created. Fig. 1 shows the measurement data of a resistor with a resistance of 1 MΩ over a frequency range from 10 kHz up to 30 MHz. The resistance locus diagram shows a behavior like a capacitive shunt circuit. The reactance of a surface-mount resistor could not be neglected, even for low frequencies, like a few MHz. Every resistor used in the oscillator was measured. The measurement data show that for increasing resistance values the reactance part will also increase. This means, every resistor used in the crystal oscillator has to be described with a model, containing a resistance and a reactance component.
For simulations, a commercial harmonic balance simulator is used. A common way to include measurement data in this kind of simulators is to use so-called S-Parameter-files. The resistor can be described as a one-port-device. Therefore a one-port S-Parameter-file (S1P-file) is used. This S-Parameter file contains the scattering parameter of a component measured over frequency. For every resistor value used in the crystal oscillator the S-Parameter files were constructed and used for simulations.

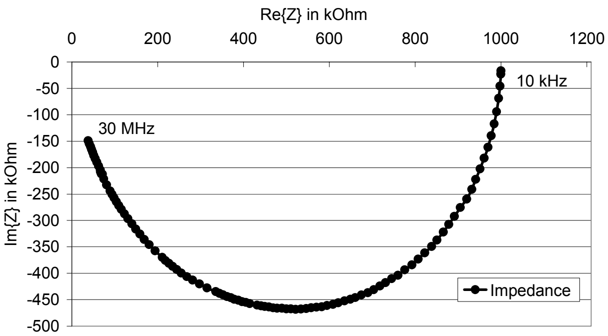

Figure 1: Impedance locus diagram of a 1 MΩ resistor measured over frequency. Start frequency is 10 kHz and the stop frequency is 30 MHz.

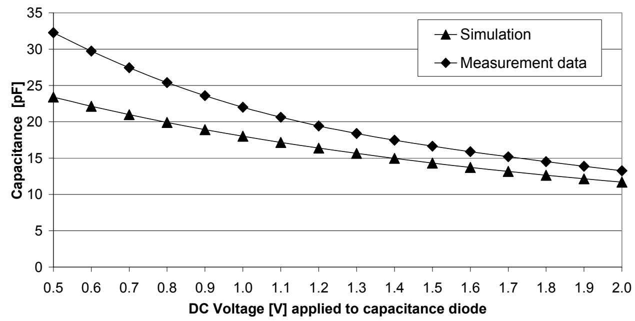

Figure 2: Simulated and measured capacitance of the diode in use

B. Modeling the capacitance diode

The crystal oscillator used in cell phone applications contains a capacitance diode to control the frequency of the crystal oscillator. To determine the initial frequency and the tuning behavior of the crystal oscillator, a precise modeling of the capacitance characteristic has to be achieved.

Available SPICE-models for capacitance diodes are only valid for small-signal applications. A good match between simulation data and measurement results could be achieved only for small-signal applications. This means the AC voltage swing across the capacitance diode is small compared to the applied DC voltage.

In a crystal oscillator used for cell phone applications, normally large-signal conditions predominate. In Fig. 2, simulation data and measurement results for large-signal conditions are presented. The applied AC voltage swing during the measurement complies with AC voltage swing measured in the oscillator.

Fig. 2 shows a large discrepancy between simulation results and measurement data. Especially for low DC voltages the measurement data show a larger capacitance value than the simulation predicts. This results in a lower frequency of the crystal oscillator than expected. This frequency shift is in the range of several hundred ppms.

Fig. 3 shows the series resistance of the capacitance diode measured over DC voltage. For DC voltages below 1 V the series resistance increased up to 60 Ω. With this measurement result, it was obviously necessary to model the series resistance of the capacitance diode not only with a constant resistor value but also by a voltage dependent resistor. In normal SPICE-models the series resistor of a capacitance diode is described by a resistor value of a few ohms. This is true for this capacitance diode, if the applied DC voltage is larger than 1 V. But for applied DC voltages lower than 1 V, the resistance is not negligible and has to be modeled with a voltage dependency.

Therefore, a new behavior model of the capacitance diode was created. This model contains a voltage dependent capacitor and a voltage dependent resistor in a serial connection. Fig. 4 shows the model, used for the capacitance diode. Equation (1) is a fifth order polynomial used for modeling the diode capacitance. The coefficient values for this fifth order polynomial were determined by curve fitting, using the method of least squares fit.

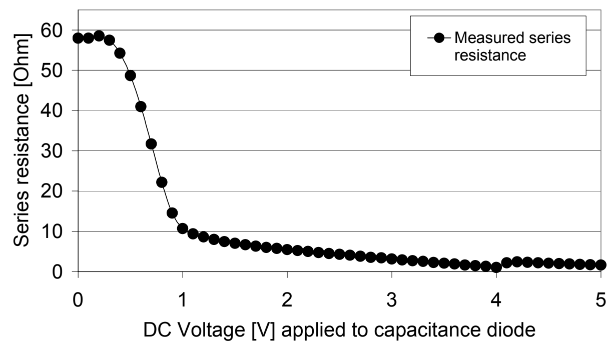

Figure 3: Measured series resistance of the capacitance diode in use.

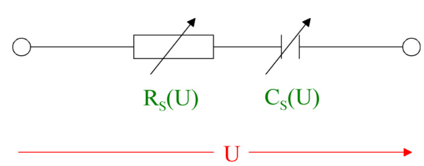

Figure 4: Behavior model of the capacitance diode. The series resistance and the capacitance were modeled as function of the applied DC voltage.

$$C_S(U) = \sum_{I=0}^{5} a_i U^i \qquad (1)$$

The voltage dependent resistor was also modeled by a fifth order polynomial. As mentioned before, the resistance value increased for DC voltages below 1 V. Therefore two different fifth order polynomials were used to model the series resistance of the capacitance diode. The coefficients of both polynomials were determined in such a way that at 1 V the function was continuous. Equations (2) and (3) are used for modeling the series resistance of the capacitance diode.

$$R_{S1}(U) = \sum_{I=0}^{5} b_i U^i \qquad U \leq 1V \qquad (2)$$

$$R_{S2}(U) = \sum_{I=0}^{5} c_i U^i \qquad U > 1V \qquad (3)$$

C. Modeling the stray capacitances

In typical cell phone applications a multi-layer printed circuit board (PCB) is used. Normally the crystal oscillator is mounted either on the top layer or on the bottom layer of such a circuit board. Some of the inner layers are used to provide the grounding of the circuit. After performing a circuit analysis, different several pads can be identified to have stray capacitances against the ground layer. The stray capacitances differ from 0.23 pF up to 1 pF depending on the pad geometry and the distance between the pad and the ground layer. The stray capacitances were measured and also simulated with a field simulator. The different stray capacitances are modeled by discrete capacitors. These capacitors were also included in the simulation, closely to those components, whose pads caused this stray capacitance.

IV. Results

To investigate, if the modeled components will improve the accuracy of our simulation, a comparison between measurement data and simulation results were done. One parameter was the initial frequency of various oscillators. Therefore, in five different oscillators the crystals were measured and every crystal was described by its own equivalent circuit diagram. The transistor was modeled by a SPICE-model, provided by the transistor supplier. The resistors and the capacitance diode were modeled using the above described behavior models. Also the different stray capacitances were included in the simulation. Table 1 shows the simulation and measurement results. A good match between simulation and measurement could be achieved. The difference is in the interval of ± 2 ppm.

Table 1: Comparison between simulation result and measurement data. Compared parameter was the initial frequency of five crystal oscillator. Applied DC voltage was 1.3 V

	Initial frequency measured f_{meas} [MHz]	Initial frequency calculated f_{sim} [MHz]	Difference f_{meas} and f_{sim} [ppm]
No. 1	26,000064	26,000105	**1,57**
No. 2	26,000109	26,000071	**-1,46**
No. 3	26,000066	26,000118	**2,00**
No. 4	26,000045	26,000091	**1,77**
No. 5	25,999944	25,999987	**1,65**

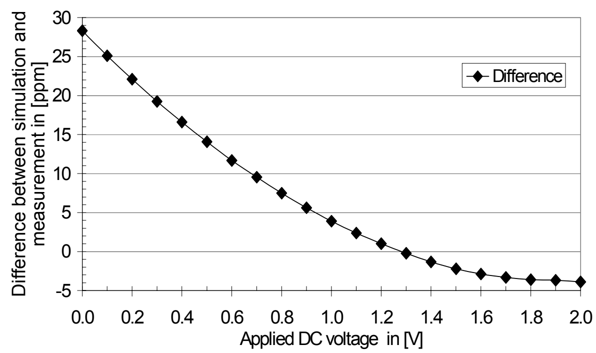

Figure 5: Difference between simulation and measurement of frequency of oscillation for different applied DC voltages.

Afterwards, the applied DC voltage was varied at the capacitance diode. The measured frequency of oscillation and the simulation results were compared. Fig. 5. shows the difference between simulation and measurement.

For applied DC voltages larger than 1.3 V, the difference between simulation and measurement is in the range of -4 ppm. But for applied DC voltages below 1.0 V the difference increases drastically.

Several reasons could be identified. First of all, the depletion layer thickness of the capacitance diode will be reduced when the positive half-wave of the AC voltage occurs. This will have impact on the capacitance of the diode, the capacitance will increase, because the depletion layer became smaller. A second reason can be found in the modeling of the diode. The diode was modeled with an AC voltage swing of 1 V, but: the voltage drop across different components in the circuit will vary with the DC voltages, because the capacitance of the diode changes. This means the behavior model of the capacitance diode has to be improved for lower DC voltages by extending the models for the capacitance and resistance to describe the dependence on the different applied AC voltages.

V. Conclusion

A number of circuit components were identified to improve the accuracy of the simulation. Special attention was turned to the resistors in use and the capacitance diode.

The simulation accuracy could be improved by describing the resistors with a reactive part even for low frequencies like a few MHz.

The capacitance diode was also described by a model for large signal behavior. This model consists of a voltage dependent resistor and a capacitor. The resistance and capacitance were modeled using a fifth order polynomial equation. A good match between simulation and measurement could be achieved for the specified DC operating point of the capacitance diode. For larger applied DC voltages a good match between simulation and measurement could be found, but for lower DC voltages the differences between simulation and measurement increased drastically. Therefore the behavior model of the capacitance diode has to be improved, by adding an AC voltage dependency of the capacitance and the series resistance of the diode.

Further investigations will focus on the validation of the capacitance diode model for different AC voltages and DC voltages. The capacitance diode has also to be described by a "non-behavior model", i.e., components with physical representation should be used.

Simulations of the temperature dependency of a crystal oscillator will be a further target. Therefore, the temperature dependency of the capacitance diode has to be included. Also the transistor model has to be improved.

ACKNOWLEDGMENT

The authors would like to thank Siemens AG for supporting their work.

REFERENCES

[1] D. Hildenhagen, *Simulation eines Quarzoszillators mit ADS*, Dipl.-Ing.-Thesis Gerhard-Mercator-Universität Duisburg, 2002

[2] B. Neubig and W. Briese, *Das grosse Quarzkochbuch,* Franzis-Verlag, Feldkirchen, 1997

[3] Application note APN1004, *Varactor SPICE models for RF VCO applications*, Skyworks (former Alpha Industries)

[4] ADS 2002, Online Manual, Agilent Technologies