# Computer Modeling of RF MEMS Inductors Using SPICE

Elissaveta Gadjeva

*Abstract* – **Computer models are developed for RF MEMS inductors. They are implemented in the general purpose circuit simulator Cadence PSpice. Parameterized inductor macromodels are developed taking into account the frequency dependence of the series resistance due to the skin-effect. An automated procedure for parameter extraction of MEMS inductor model is developed. The procedure is realized in the environment of Cadence Capture and Cadence PSpice, using macrodefinitions in the graphical analyzer Probe.**

*Keywords* – **RF MEMS inductors, PSpice simulator, Computer models.**

## I. INTRODUCTION

With the recent development of wireless communications, there is a growing demand for integrated RF circuits with high performance and low cost. Various micromachining technologies, implemented in microelectromechanical systems (MEMS), have been applied to RF applications. Micro inductors are important passive components applied in LC tank, VCO and DC-DC converters [1,2]. The MEMS technology allows to enhance the *Q*-factor of micro inductors, to increase the selfresonant frequency and to decrease the energy dissipation in inductors [1-5].

In the present paper, computer models are developed for RF MEMS inductors. They are implemented in the general purpose circuit simulator *Cadence PSpice* [6]. An automated procedure for parameter extraction of MEMS inductor model is developed. The procedure is realized in the environment of *Cadence Capture* and *Cadence PSpice*, using macrodefinitions in the graphical analyzer *Probe*.

## II. RF MEMS INDUCTOR MODELS

The $\Pi-$ RF physical inductor model shown in Fig. 1 [7,8] describes the performance of a MEMS inductor, where $L_s$ is the inductance, $C_s$ is the capacitance between the windings of the inductor, $C_1$ is the capacitance in the oxide (or polyamide) layer between the coil and the silicon substrate, $C_p$ is the capacitance between the coil and the ground through the silicon substrate, and $R_p$ is the eddy current losses in the substrate [1]. The series resistance $R_s$ is assumed constant up to frequency $f_o$ and then increases as $\sqrt{f}$ to model the skin-effect (Fig. 2), where *f* is in GHz:

$$R_s(f) = \begin{cases} R_{so} & \text{for } f < f_o \\ A\sqrt{f} & \text{for } f \ge f_o \end{cases} \tag{1}$$

A simplified variant of the model shown in Fig. 1 is presented in Fig. 3.

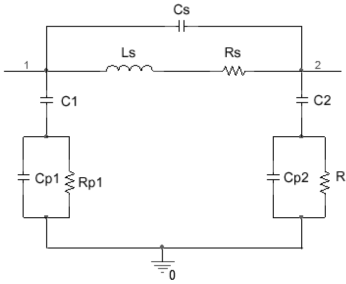

Fig. 1. $\Pi$ model of MEMS inductor

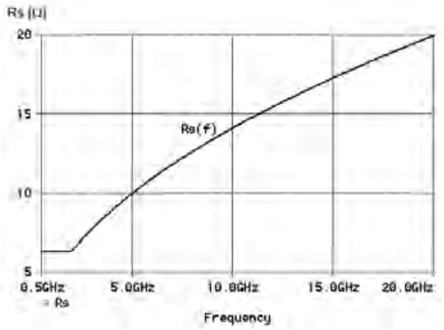

Fig. 2. Frequency dependence of the series resistance $R_s$

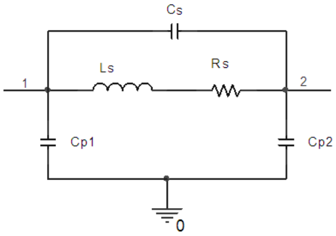

Fig. 3. Simplified $\Pi$ model of MEMS inductor

The high performance solenoid-type MEMS inductor is modeled by the equivalent circuit shown in Fig. 3 [3], where the frequency dependence of $R_s$ due to the skin-effect is represented by the dependence:

$$R_s(f) = A\sqrt{f} \ . \tag{2}$$

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## III. COMPUTER RELIZATION OF MEMS INDUCTOR MODELS

The *PSpice* model corresponding to the equivalent circuit shown in Fig. 3 is presented in Fig. 4.

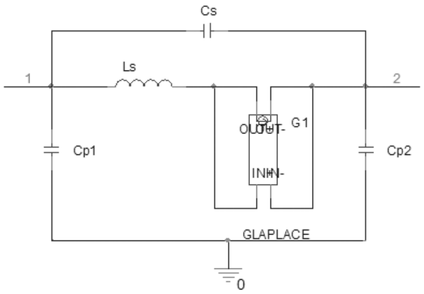

Fig. 4. *PSpice* model corresponding to the equivalent circuit in Fig. 3

The frequency dependence of $R_s$ is defined by the voltage controlled current source (VCCS) G1 of GLAPLACE type using the expression (1). It is realized in the form:

$$R_s(f)=KR_{so}+(1-K)A\sqrt{f}\,, \tag{3}$$

where

$$K=\begin{cases}1 & \text{for } f<f_o\\ 0 & \text{for } f\geq f_o\end{cases}\,. \tag{4}$$

As the frequency *f* is not directly accessible for the user in the input language of the *PSpice* simulator, the LAPLACE variable s= j$\omega$ is used for obtaining the frequency in (3). The coefficient *K* is calculated in the parameterized macromodel, defined using block, according to the input language of the PSpice simulator in the form:

0.5*(sgn(@Fo-M(s)/6.283165)+1)

where M(s) is used to obtain the angular frequency $\omega$.

The admittance $1/R_s$ calculated using (3) and (4), is defined in the property XFORM of the VCCS as follows:

{@Rso*0.5*(sgn(@Fo-M(s)/6.283165)+1)+
0.5*(sgn(M(s)/6.283165-@Fo)+1)*@Rso/sqrt(1E-9*@Fo)*
sqrt(1E-9*M(s)/6.283165)}

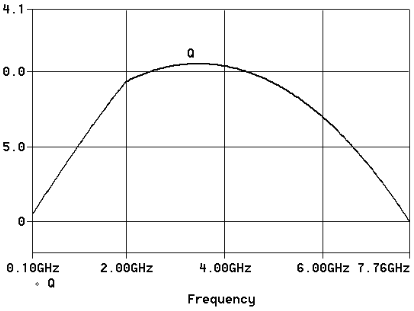

Fig. 5. Simulated *Q* factor

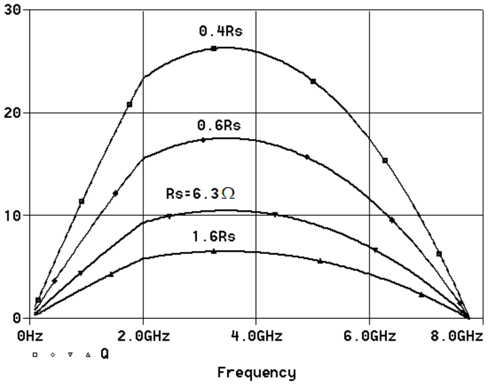

Fig. 6. Dependence of *Q* on $R_s$

The simulated Q factor of the inductor with $L_s$=5 nH, $C_{p1}=C_{p2}$ = 75 fF, $C_s$ = 9 fF, $R_{so}$ = 6.3 $\Omega$ and fo = 2 GHz is presented in Fig. 5. Using parametric sweep, the simulation results for the dependence of Q on Rs are shown in Fig. 6.

Using *File/Append* option of the graphical analyzer *Probe*, the results for the dependence of *Q* on $C_s$ and $C_p$ variation are presented together on the same plot as shown in Fig. 7. The curve 1 corresponds to 0.2$C_p$ and 0.4$C_s$, curve 2 – to 0.4$C_p$ and 0.6$C_s$, curve 3 – to 0.6$C_p$ and 0.8$C_s$, curve 4 – to $C_p$ and $C_s$, curve 5 – to 1.6$C_p$ and 1.4$C_s$. The simulated results are in agreement with the results given in [1].

The *PSpice* realization of the solenoid-type RF MEMS inductor model shown in Fig. 3 [3] is presented in Fig. 8.

The frequency dependence of $R_s$ is defined by equation (2), where $A$ = 1.503. The admittance 1/$R_s$ is defined in the property XFORM of VCCS:

{1/(1.503*sqrt(1E-9*M(s)/6.283185))}

The simulation results for the quality factor *Q* and inductance *L* are presented in Fig. 9. They are in a good agreement with the measured results given in [3].

The calculated impedance Zeq of the air suspended RF MEMS inductor represented by the model shown in Fig. 1 [4] is shown in Fig. 10. The model parameters are: Cs=1.14 fF, $L_s$=6.76 nH, $R_1$= 1$\Omega$, $C_1$=11.6 fF, $C_2$=90.5 fF, $C_{p1}$=1 fF , $C_{p2}$=10.2 fF, $R_{p1}$=275$\Omega$, $R_{p2}$=332$\Omega$.

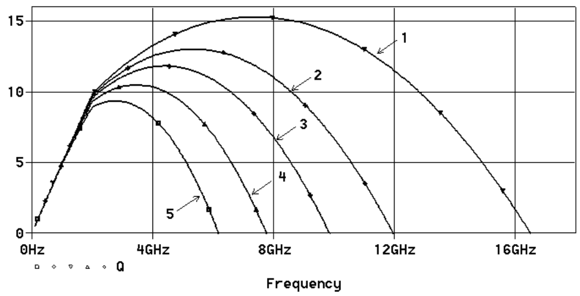

Fig. 7. Dependence of *Q* on $C_s$ and $C_p$ variation

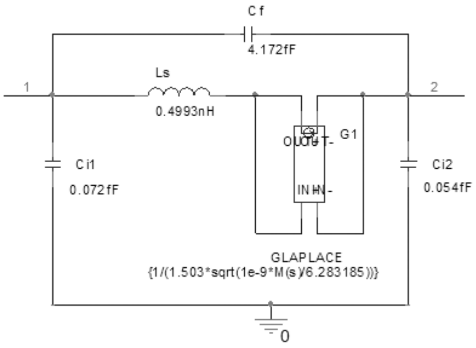

*Fig. 8. PSpice* realization of the solenoid-type RF MEMS inductor model

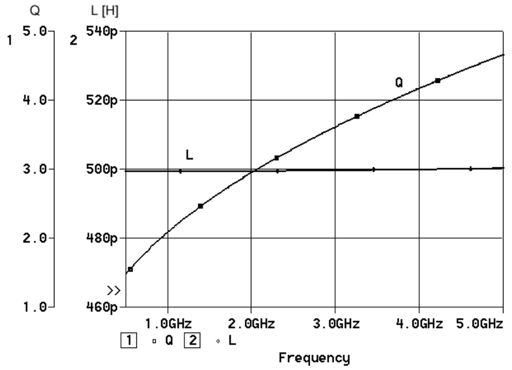

Fig. 9. Simulation results for the quality factor *Q* and inductance *L*

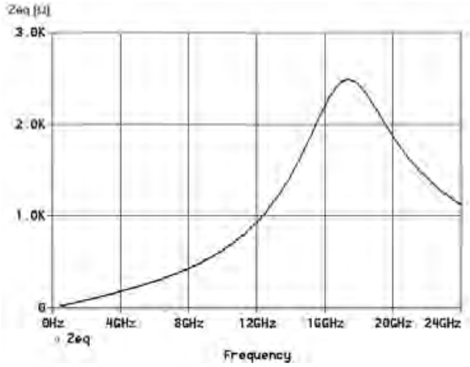

Fig. 10. The impedance $Z_{eq}$ of the air suspended RF MEMS inductor

## IV. PARAMETER EXTRACTION OF RF MEMS MODEL

An automated procedure for parameter extraction of MEMS inductor model is developed based on two-port measured *S*-parameters. The procedure is realized in the environment of *Cadence Capture* and *PSpice*, using macrodefinitions in the graphical analyzer *Probe*.

The equivalent circuit of a fully compatible, highly suspended spiral inductor is presented in Fig. 11 [5].

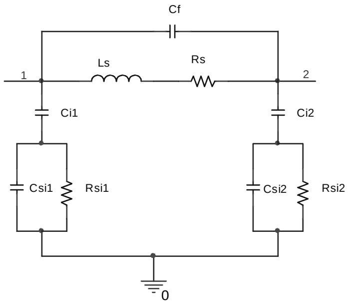

Fig. 11. Equivalent circuit of a fully compatible, highly suspended spiral inductor

The two-port measured S-parameters are used as input data. They are defined using voltage controlled current sources VCCS of GFREQ type (Fig. 12). The table is in the form:

<frequency,magnitude [DB], phase [DEG]>:
(freq1,mag1,phase1), (freq2,mag2,phase2) …

The measured S-parameters are obtained in the form of corresponding node voltages (Fig. 12). They are defined using the following macrodefinitions in the graphical analyzer *Probe*:

S11=V(S_11) S21=V(S_21)
S12=V(S_12) S22=V(S_22)

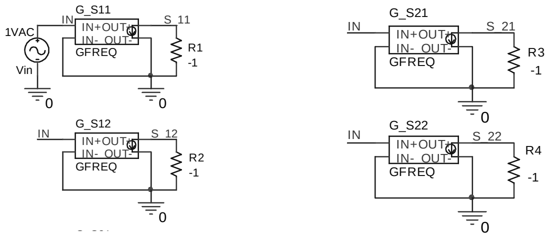

Fig. 12. Introducing the measured S-parameters in PSpice

The extraction procedure is realized in the following steps:

1. Conversion of two-port *S*-parameters $S_{ij}$ in two-port Y-parameters

The measured two-port *S*-parameters $S_{ij}$ are converted to the two-port *Y*-parameters $Y_{ij}$, $i,j$ = 1,2, needed for the parameter extraction procedure.

$$Y_{11} = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{\Delta}, \tag{5}$$

$$Y_{22} = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{\Delta}, \tag{6}$$

$$Y_{12} = \frac{-2S_{12}}{\Delta} \quad ; \quad Y_{21} = \frac{-2S_{21}}{\Delta}, \tag{7}$$

where

$$\Delta = ((1+S_{11})(1+S_{22})-S_{12}S_{21})R_o \ .$$

$R_o$ =50 Ω - the characteristic impedance.

2. Determination of $L_s$

$L_s$ is obtained from the parameter $Y_{12}$ at low frequency $f_l$. :

$$L_{sf}(f)=\frac{\left|\mathrm{Im}\left[1/Y_{12}\right]\right|}{\omega}\;;\;L_s=\min\left(L_{sf}(f)\right) \qquad (8)$$

3. Determination of the coefficient $A$

The coefficient $A$ is calculated from (2) using the resistanve value $R_s(f_o)$ for the frequency $f_o$

$$R_{sf}(f)=\left|\mathrm{Re}\left[1/Y_{12}\right]\right|\;;\;R_s=R_{sf}(f_o)\;;\;A=R_s\big/\sqrt{f_o} \qquad (9)$$

4. Determination of $C_{i1}$, $C_{i2}$ at low frequency $f_l$.

$$C_{i1}=-\frac{1}{\omega\mathrm{Im}\left[1/\left(Y_{11}+Y_{12}\right)\right]},\quad C_{i2}=-\frac{1}{\omega\mathrm{Im}\left[1/\left(Y_{22}+Y_{12}\right)\right]} \qquad (10)$$

5. Determination of $C_{si1}$ and $C_{si2}$ at high frequency $f_h$

$$C_{si1}=\frac{1}{\omega}\frac{1}{\dfrac{1}{Y_{11}+Y_{12}}-\dfrac{1}{\mathrm{j}\omega C_{i1}}},\quad C_{si2}=\frac{1}{\omega}\frac{1}{\dfrac{1}{Y_{22}+Y_{12}}-\dfrac{1}{\mathrm{j}\omega C_{i2}}} \qquad (11)$$

6. Determination of $R_{si1}$ and $R_{si2}$ at high frequency $f_h$

$$R_{si1}=\mathrm{Re}\left[\frac{1}{Y_{11}+Y_{12}}-\frac{1}{\mathrm{j}\omega C_{i1}}\right]^{-1},\quad R_{si2}=\mathrm{Re}\left[\frac{1}{Y_{22}+Y_{12}}-\frac{1}{\mathrm{j}\omega C_{i2}}\right]^{-1} \qquad (12)$$

7. Determination of $C_f$ at high frequency $f_h$

$$Y_f=-Y_{12}-\frac{1}{R_s(f)+\mathrm{j}\omega L_s}\;;\quad C_f=\frac{1}{\omega}\mathrm{Im}\left[Y_f\right]. \qquad (13)$$

The extracted parameter values for the MEMS inductor developed in [5] are presented in Table I. The parameter values obtained in [5] are also given. The calculated parameters are in a very good agreement with to the model parameter values and the measured results given in [5].

## V. CONCLUSIONS

Computer *PSpice* models of RF MEMS inductors have been developed. The frequency dependence of the series resistance due to the skin-effect is taken into account. An automated parameter extraction procedure for MEMS inductor model is developed.

## ACKNOWLEDGEMENT

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TABLE I. EXTRACTED PARAMETER VALUES

| **Model parameter** | ***Extracted parameter value*** | ***Parameter value obtained in [5]*** |
|---|---|---|
| *Ls* | 1.34nH | 1.34nH |
| *A* | 0.27 | 0.27 |
| *Cs*1 | 11.6fF | 11.6fF |
| *Cs*2 | 90.5fF | 90.41fF |
| *Csi*1 | 1.012fF | 1fF |
| *Csi*2 | 10.2fF | 10.2fF |
| *Rsi*1 | 275 Ω | 275.01 Ω |
| *Rsi*2 | 331.92 Ω | 332 Ω |
| *Cf* | 1.139fF | Cf=1.14fF |

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