Automated Parameter Extraction of Geometry Dependent RF Planar Inductor Model

Vladislav P. Durev, Elissaveta D. Gadjeva and Marin H. Hristov

***Abstract*—An approach is proposed in the present paper to parameter extraction of geometry dependent RF planar spiral inductor model. A direct extraction procedure is developed and realized in the *Cadence PSpice* and *Cadence Probe* environment based on the measured two-port *S*-parameters. To minimize the error for the full range of operation a Genetic Algorithm (GA) optimization procedure is applied in MATLAB environment. The approach is useful in RF model design, as the *S*-parameters can be easily measured for a given microelectronic technology. The proposed model extraction approach is characterized by a very good accuracy.**

***Index Terms*— Planar spiral inductors; RF model; Parameter extraction; S-parameters; Genetic Algorithm**

I. INTRODUCTION

WITH the fast development of the RF and wireless technologies, the need of accurate behavioral modeling, simulation and extraction approaches increases. The most used building components of RF chips are the planar inductors and planar transformers. The accuracy of the developed models and parameter extraction approaches plays critical role in the present RF microelectronic design process.

The physical model of planar spiral inductor on silicon [1] is a very popular model used in RF microelectronic design. Its model parameter values can be expressed directly using the geometry of the spiral inductor. The skin effect at high frequencies is modeled using a frequency dependent series resistance. Several extraction procedures are developed for the physical spiral inductor model – direct procedures [2], optimization based procedures [3]. A number of approaches to geometry optimization of spiral inductors are proposed based on geometric programming optimization [4], parametric analysis [5], etc.

In the present paper an approach is developed to direct parameter extraction based on the measured two-port *S*-parameters. The approach gives excellent results for frequencies around the working frequency. Genetic Algorithm (GA) [6] based approach in the MATLAB environment is used to refine the simulated *S*-parameters and to minimize the post extraction errors for the full investigated frequency range.

II. DIRECT PARAMETER EXTRACTION OF THE PHYSICAL MODEL OF SPIRAL INDUCTOR IN PSPICE

A. Analysis of the spiral inductor model

The physical model of spiral inductor [1] is shown in Fig. 1. The model parameters are R_s, R_{si}, C_s, C_{ox}, C_{si} and L_s. The series resistance takes into account the skin depth of the conductor. L_s is the inductance of the spiral, C_{ox} represents the capacitance between the spiral and the substrate. R_{si} and C_{si} model the resistance and the capacitance of the substrate, and C_s models the parallel-plate capacitance between the spiral and the center-tap underpass. The presented extraction procedure is based on the measured two-port *S*-parameters.

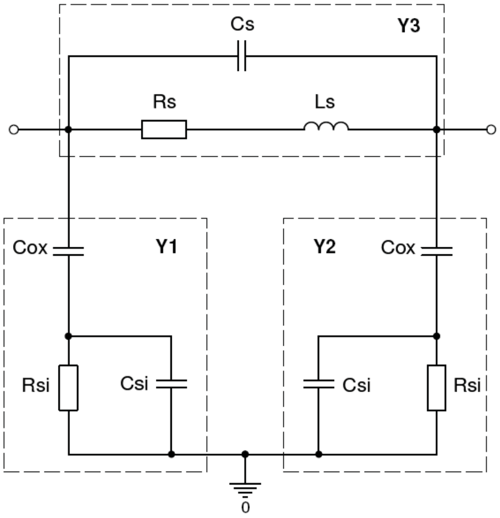

Fig. 1. Physical model of spiral inductor.

As the model parameters can be easily expressed by the two-port *Y*-parameters, the measured *S*-parameters S_{ijm} are converted to *Y*-parameters Y_{ijm}, $i,\ j = 1,\ 2$. The model parameter extraction procedure consists of the following steps:

1. *S*- to *Y*- two-port parameter transformation:

$$Y_{11m} = Y_0 \frac{1 - S_{11m}^2 + S_{12m}^2}{\left(1 + S_{11m}\right)^2 - S_{12m}^2} \ ; \ Y_{12m} = Y_0 \frac{-2S_{12m}}{\left(1 + S_{11m}\right)^2 - S_{12m}^2}, \qquad (1)$$

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V. P. Durev is with the Department of Electronic Engineering, Technical University of Sofia; 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria,e-mail: v_p_durev@yahoo.com

E. D. Gadjeva is with the Department of Electronic Engineering, Technical University of Sofia; 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: egadjeva@tu-sofia.bg

M. H. Hristov is with the Department of Microelectronics, Technical University of Sofia; 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: mhristov@ecad.tu-sofia.bg

where $Y_{22m} = Y_{11m}$ due to the symmetry of the equivalent circuit and $Y_{21m} = Y_{12m}$ due to the passivity. $Y_0 = 1/R_0$ where R_0 is the characteristic resistance.

The parameter extraction procedure is based on determination of the admittances Y_1, Y_2 and Y_3 (Fig. 1) as a function of the two-port Y-parameters:

$$Y_1 = Y_2 = Y_{11m} + Y_{12m} \;;\; Y_3 = -Y_{12m} \tag{2}$$

The next step is to express the admittances Y_1 and Y_3 as well as the corresponding impedances Z_1 and Z_3 by the model parameters as follows:

$$Y_1 = \frac{1}{\dfrac{1}{j\omega C_{ox}} + \dfrac{R_{si}}{1 + j\omega R_{si} C_{si}}} \tag{3}$$

$$Z_1 = \frac{1}{Y_1} = \frac{R_{si}}{1 + \left(\omega R_{si} C_{si}\right)^2} - j\left[\frac{1}{\omega C_{ox}} + \frac{\omega R_{si}^2 C_{si}}{1 + \left(\omega R_{si} C_{si}\right)^2}\right] \tag{4}$$

$$Y_3 = j\omega C_s + \frac{1}{R_s + j\omega L_s} \tag{5}$$

$$Y_3 = \frac{1}{Z_3} = \frac{R_s}{R_s^2 + \left(\omega L_s\right)^2} + j\omega\left[\frac{\left(\omega L_s\right)^2 C_s - L_s + R_s^2 C_s}{R_s^2 + \left(\omega L_s\right)^2}\right]. \tag{6}$$

2. Determination of R_s and L_s

The influence of the capacitance C_s can be neglected for low frequencies ($f = f_l$). Thus from (5) for the impedance Z_3 for low frequencies can be written:

$$Z_{3l} \approx R_s + j\omega_l L_s \tag{7}$$

$$R_s = \Re\left(Z_{3l}\right) \;;\; L_s = \Im\left(Z_{3l}\right)/\omega_l\,. \tag{8}$$

3. Determination of R_{si} and C_{ox}

Using (4), for low frequencies

$$R_{si} \approx \Re\left(Z_{1l}\right) \;;\; C_{ox} \approx -\frac{1}{\omega_l \Im\left(Z_{1l}\right)}. \tag{9}$$

4. Determination of C_{si}

The inequality $\omega_h R_{si} C_{si} >> 1$ is valid for high frequencies ($f = f_h$). Using (4)

$$\Im\left(Z_{1h}\right) \approx -\left(\frac{1}{\omega_h C_{ox}} + \frac{1}{\omega_h C_{si}}\right). \tag{10}$$

Hence

$$C_{si} \approx -\frac{1}{\omega \Im\left(Z_{1h}\right) + \dfrac{1}{C_{ox}}}. \tag{11}$$

5. Determination of the series resistance R_{sw} at the working frequency f_w. The skin effect is taken into account using (6) for $f = f_w$. The series resistance is

$$R_{sw} \approx R_s\left(f_w\right) = \Re\left[Y_3\left(f_w\right)\right]. \tag{12}$$

The inequality $\omega_w L_s >> R_{sw}$ is valid for f_w. As a result

$$R_{sw} \approx \left(\omega_w L_s\right)^2 \Re\left(Y_{3w}\right). \tag{13}$$

For the resonant frequency ($f = f_0$) $\Im\left(Y_3\right) = 0$. Hence the value of the capacitance C_{sw} is obtained from (6) for the working frequency f_w in the form:

$$C_{sw} \approx \frac{L_s}{\left(\omega_0 L_s\right)^2 + R_{sw}^2}. \tag{14}$$

The value of the capacitance C_s for the whole frequency range can be obtained at the highest frequency of the range using (6) in the form:

$$C_s = \frac{1}{\omega_h}\left[\Im\left(Y_3\right) + \frac{\omega_h L_s}{R_s^2 + \left(\omega_h L_s\right)^2}\right]. \tag{15}$$

The series resistance R_s in Fig. 1 is frequency dependent. If the geometry of the extracted spiral inductor is known R_s can be calculated using the formula [1]:

$$R_s = \frac{l}{\sigma w \delta\left(1 - e^{-t/\delta}\right)}, \tag{16}$$

where w is the width of the metal strips(14.5μm), δ is the skin-effect depth into the metal layers, σ is the conductivity of metal layers (3.34×10^7 S/m), l is the length of the spiral $l = 4n\left(D_{in} + D_{out}\right)/2$, t is the thickness of the metal layer of the spiral (2μm), D_{in} is the inner spiral diameter, D_{out} is the outer spiral diameter, n is the number of turns [1]. The series resistance R_s is modeled according to the input language of the *PSpice* simulator using the element voltage controlled current source (VCCS) GLAPLACE from the ABM.lib [7].

In case when the geometry of the spiral inductor is not known R_s can be calculated using the formula [8]:

$$R_s = R_0\left(1 + K_1 f^{K_2}\right), \tag{17}$$

where the coefficients K_1 and K_2 determine the frequency dependence of R_s. The resistance R_0 in (17) can be calculated using (8). K_1 and K_2 can be calculated from two values for R_s – for the lowest frequency (expression (8)) and for the working frequency (expression (12)):

$$R_s(f_l) = R_0 + K_1^{'} f^{K_2} \;;\; R_s(f_w) = R_0 + K_1^{'} f^{K_2}, \tag{18}$$

where $K_1^{'} = R_0 K_1$. The obtained linear system of two equations can be solved for K_1 and K_2 straightforward.

B. PSpice realization of the extraction procedure of model parameters of planar inductors

The computer realization of the proposed extraction procedure is performed in the *Cadence PSpice* and *Cadence Probe* environment. The real and the imaginary parts of the measured *S*-parameters are introduced in the *PSpice* model using EFREQ elements from the library ABM.lib. As a result, S_{11} and S_{12} are represented in the form of signals V(S11) and V(S12) and transferred to the graphical analyzer *Probe*.

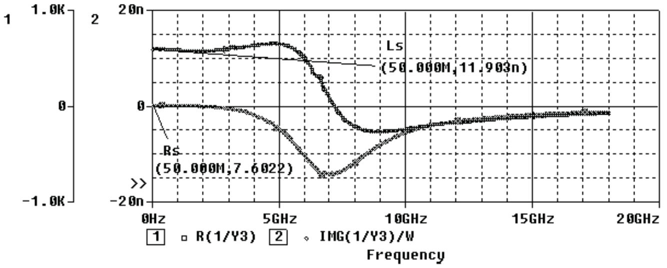

Fig. 2. Determination of R_s and L_s for low frequencies in *Probe*.

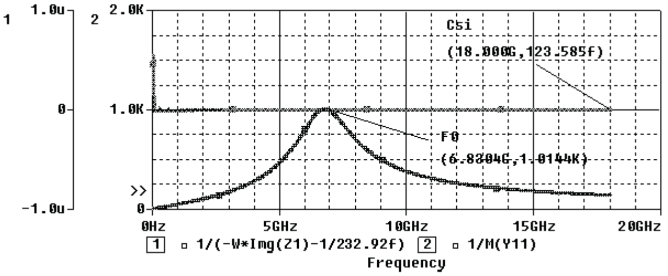

Fig. 3. Determination of C_{si} for high frequencies and the resonant frequency f_0 in *Probe*.

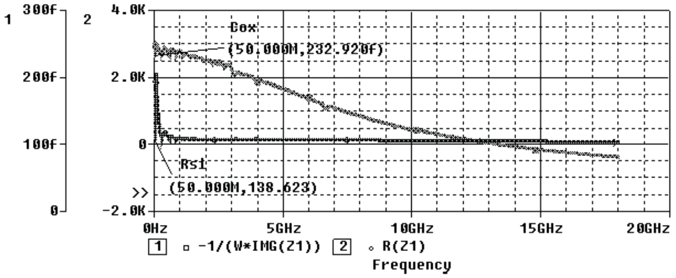

Fig. 4. Determination of R_{si} and C_{ox} for low frequencies in *Probe*.

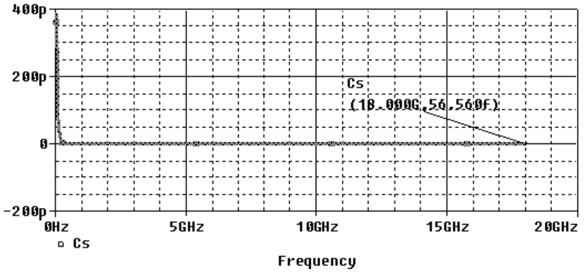

Fig. 5. Determination of C_s for high frequencies in *Probe*.

The developed extraction procedure is realized using corresponding macrodefinitions in *Cadence Probe* [9].

For the case of $6.5 \times 60 \times 14.5 \times 2$ (number of turns × inner radius (μm) × metal width (μm) × spacing (μm)) planar inductor, manufactured using 0.18 μm CMOS process, $R_0 = 50\Omega$, investigated in the frequency range of ($f_l = 50$MHz, $f_h = 18$GHz) and with the maximal value of the Q-factor $Q_{\max} = 6.5$ at the working frequency of $f_w = 1.09$GHz, the macros are in the form:

```
FL=50MHz
FH=18GHz
Fw=1.09GHz
S11m=V(S11)
S12m=V(S12)
pi = 3.14159265358
W=2*pi*Frequency
```

- Step 1: $S \rightarrow Y$ transformation (1) ÷ (4):

```
A=(1+S11m)*(1+S11m)-S12m*S12m
Y1 = (1/R0)*((1-S11m*S11m+S12m*S12m)-2*S12m)/A
Y3 = (1/R0)*2*S12m/A
Z1=1/Y1
```

- Step 2: Determination of R_s and L_s at the lowest frequency f_l (8):

```
Rs = YatX(R(1/Y3),FL)
Ls = YatX(IMG(1/Y3)/W,FL)
```

- Step 3: Determination of R_{si} and C_{ox} at the lowest frequency f_l (9):

```
Rsi = YatX(R(Z1),FL)
Cox = YatX(-1/(W*IMG(Z1)),FL)
```

- Step 4: Determination of C_{si} at the highest frequency f_h (11):

```
Csi = 1/(max(-W*Img(Z1))-1/Cox)
```

- Step 5. Determination of R_{sw} and C_{sw} at f_w using the resonance frequency f_0 (13), (14):

```
F0 = CenterFrequency(1/M(Y11),1)
W0=2*pi*F0
Rsw=4*pi*pi*Fw*Fw*Ls*Ls*YatX(R(Y3),Fw)
Csw = Ls/(4*pi*pi*F0*F0*Ls*Ls+Rsw*Rsw)
```

- Step 6. Determination of C_s for the whole investigated frequency range (15) using (16) to calculate the resistance R_s:

```
sigma = 3.34e+7
mju = 1.256e-6
delta = sqrt(2/(W*sigma*mju))
n = 6.5
ww = 14.5e-6
sp = 2e-6
t = 2e-6
Din = 120e-6
Dout = Din + 2*(n*(sp + ww) - sp)
l = 4*n*((Din+Dout)/2)
Rss = l/(sigma*ww*delta*(1 - EXP(-t/delta)))
Cs = (1/W)*(IMG(Y3) + ((W*Ls)/((Rss*Rss) + (W*W*Ls*Ls))))
```

An example of the extraction of R_s and L_s for low frequencies is shown in Fig. 2 and an example of the extraction of C_{si} for high frequencies and the determination of the resonant frequency f_0 of the spiral inductor is shown in Fig. 3. The extraction of components R_{si} and C_{ox} for low frequencies is shown in Fig. 4 and the extraction of C_s for high frequencies is shown in Fig. 5.

The results for the model parameters after the application of the described direct extraction procedure are given in Table I.

C. Error Estimation

The error estimation of the parameter extraction procedure is given in Table II, where the capacitance C_s is calculated using expression (14) and in Table III, where C_s is calculated using (15). The relative RMS error is used over the investigated frequency range between the measured and the obtained *S*-parameters for three different geometries spiral inductors, published in [10]:

$$RMSErr_S = 100 \times \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{S_{jk}^{(m)} - S_{jk}}{S_{jk}^{(m)}}\right)^2}\ \%, \qquad (19)$$

where *j, k* = 1, 2; $S_{jk}^{(m)}$ – measured S-parameters [10]; S_{jk} – obtained *S*-parameters; *n* – number of frequency points.

Because of the determination of C_{sw} for the working frequency f_w the frequency ranges in Table II are limited. The frequency ranges in Table III are also limited due to the C_s behavior at high frequencies. To enlarge the frequency ranges a GA approach is applied to optimize the model parameter values accordingly.

III. OPTIMIZATION OF THE MODEL PARAMETERS BASED ON GA

A. Determination of the ranges for the input values

The model parameter values are varied in a certain range by the GA according to the value of its purpose function. This range is determined to be ± 20% around the values from Table I. As the capacitance C_s is determined at the working frequency, it is expected to decrease at high frequencies. This determines its broader range of variation. The variation ranges for the model parameters for three geometries spiral inductors, published in [10] are given in Table IV.

TABLE I
MODEL PARAMETER VALUES AFTER THE EXTRACTION IN PSPICE

Model Param.	Extraction Results from PSpice		
	(N × R × W × S) 6.5 × 60 × 14.5 × 2 f_w = 1.09GHz [10]	(N × R × W × S) 4.5 × 60 × 14.5 × 2 f_w = 1.81GHz [10]	(N × R × W × S) 3.5 × 60 × 9 × 7.5 f_w = 2.91GHz [10]
R_{s0}(Ω)	7.6	5.06	5.68
R_{sw}(Ω)	9.08	6.351	5.7
L_s(nH)	11.9	5.67	3.56
C_{ox}(fF)	232.92	157.02	86.78
R_{si}(Ω)	138.62	225.48	340.28
C_{si}(fF)	123.59	79.98	67.58
C_{sw}(fF)	45.76	96.04	152.99
C_s(fF)	56.56	33.16	18.4

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

TABLE II
ERROR ESTIMATION OF THE DIRECT EXTRACTION PROCEDURE IN PSPICE USING C_{SW} VALUE IN THE MODEL

Geometry (N × R × W × S) Freq. range	RMSErrS, %	
	|S_{11}|	|S_{12}|
6.5 × 60 × 14.5 × 2 50MHz ÷ 1.3GHz	2.94	1.21
4.5 × 60 × 14.5 × 2 50MHz ÷ 2.1GHz	7.02	1.85
3.5 × 60 × 9 × 7.5 50MHz ÷ 3.2GHz	10.19	4.07

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

TABLE III
ERROR ESTIMATION OF THE DIRECT EXTRACTION PROCEDURE IN PSPICE USING C_S VALUE IN THE MODEL

Geometry (N × R × W × S) Freq. range	RMSErrS, %	
	|S_{11}|	|S_{12}|
6.5 × 60 × 14.5 × 2 50MHz ÷ 4GHz	2.76	18.68
4.5 × 60 × 14.5 × 2 50MHz ÷ 7.5GHz	3.55	11.03
3.5 × 60 × 9 × 7.5 50MHz ÷ 14.4GHz	3.63	4.86

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

TABLE IV
GA VARIATION RANGES OF THE MODEL PARAMETERS

Model Param.	Geometry (N × R × W × S) 6.5 × 60 × 14.5 × 2 [10]		Geometry (N × R × W × S) 4.5 × 60 × 14.5 × 2 [10]		Geometry (N × R × W × S) 3.5 × 60 × 9 × 7.5 [10]	
	min	max	min	max	min	max
Rs(Ω)	Calculated using expression (15)					
Ls(nH)	11	13	5	6	3	4
Cox(fF)	220	250	140	170	80	100
Rsi(Ω)	100	150	200	240	330	360
Csi(fF)	100	150	50	100	40	80
Cs(fF)	1	100	1	150	1	150

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

B. Determination of the purpose function

The purpose function minimizes the difference between the measured and the obtained *Y*-parameters:

$$G_{fun} = \sum_{i=1}^{n}\left|\Re\left[Y_k(f_i)\right] - \Re\left[Y_k^{(req)}(f_i)\right]\right| + \\ + \sum_{i=1}^{n}\left|\Im\left[Y_k(f_i)\right] - \Im\left[Y_k^{(req)}(f_i)\right]\right| \qquad (20)$$

where k = 1,2,3; $Y_k(f_i)$ – current admittances (3), (5); $Y_k^{(req)}(f_i)$ – admittances obtained by *S*- to *Y*-transformation of the measured *S*-parameters; *n* – number of frequency points.

The optimization procedure is realized using the GA Toolbox [11] in MATLAB. The algorithm of the optimization procedure is shown in Fig. 6.

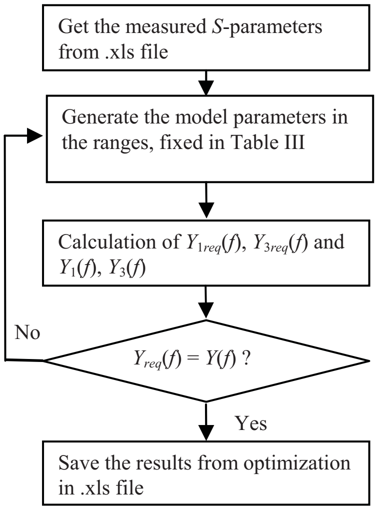

Fig. 6. Algorithm of the GA optimization procedure.

The GA procedure has the following parameters: *NIND* = 300, *MAXGEN* = 200, *NVAR* = 5, *PRECI* = 200, *GGAP* = 0.7, where *NIND* is the number of individuals, *MAXGEN* is the maximal number of iterations, *NVAR* is the number of the optimized model parameters, *PRECI* is the precision factor, and *GGAP* is the generation gap [11].

The following MATLAB program segment describes the optimization of the values of the model parameters in Fig. 1 at each frequency in the investigated frequency range. The search is controlled by the expression of the purpose function (19), using the expressions (1), (4), (6), (16):

```
   for i = 1:DATA_ROWS
   omg = 2*pi*frequency(i);
   s = j*omg;
   Rs = L/(w*sigma*delta*(1.0 - exp(-t/delta)));
   Y3req = (-1.0)*(2.0*S12req(i)*Y0/((1 + S11req(i))^2 -
S12req(i)^2));
   Y1req = Y0*(1-S11req(i)^2 + S12req(i)^2)/((1+S11req(i))^2 -
S12req(i)^2) - Y3req;
   Y1 = (s.*Cox.*(1.0 + s.*Rsi.*Csi))./(s.*Rsi.*(Cox + Csi) + 1.0);
   Y3 = (-1.0).*((s.*Rs.*Cs + s.*Ls.*s.*Cs + 1.0)./(Rs + s.*Ls));
      %Purpose function
   g_fun = g_fun + abs(real(Y1) - real(Y1req)) + abs(real(Y3) -
real(Y3req)) + abs(imag(Y1) - imag(Y1req)) + abs(imag(Y3) -
imag(Y3req));
   end
```

The obtained results and the error estimation are given in Table V and Table VI correspondingly. As the model in Fig. 1 is verified up to 10GHz [1], the values of the optimized model parameters for geometries 6.5 × 60 × 14.5 × 2 and 4.5 × 60 × 14.5 × 2 preserve their dependence on the geometry of the inductor. The model parameters for geometry 3.5 × 60 × 9 × 7.5 are optimized in the frequency range 50MHz ÷ 14.4GHz and they do not preserve the dependence on the geometry of the inductor (Table V). As a result of the GA optimization the obtained relative RMS error is less than 5%.

The comparison between the measured [10] and GA optimized results of S_{11} and S_{12} for 6.5 × 60 × 14.5 × 2 inductor is shown in Fig. 7 and the comparison between the corresponding *Q*-factors is shown in Fig. 8.

TABLE V
MODEL PARAMETER VALUES AFTER THE GA OPTIMIZATION IN MATLAB

Model Param.	Extraction Results from MATLAB		
	(N × R × W × S) 6.5 × 60 × 14.5 × 2 f_w = 1.09GHz [10]	(N × R × W × S) 4.5 × 60 × 14.5 × 2 f_w = 1.81GHz [10]	(N × R × W × S) 3.5 × 60 × 9 × 7.5 f_w = 2.91GH [10]
R_{s0}(Ω)	Calculated using expression (15)		
L_s(nH)	11.7	5.48	3.5
C_{ox}(fF)	220	140	40
R_{si}(Ω)	150	240	360
C_{si}(fF)	150	76.7	20
C_s(fF)	6.22	20	15.7

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

TABLE VI
ERROR ESTIMATION OF THE OPTIMIZATION PROCEDURE IN MATLAB

Geometry (N × R × W × S) Freq. range	RMSErrS, %	
	$\|S_{11}\|$	$\|S_{12}\|$
6.5 × 60 × 14.5 × 2 50MHz ÷ 4GHz	1.83	1.76
4.5 × 60 × 14.5 × 2 50MHz ÷ 7.5GHz	2.96	1.83
3.5 × 60 × 9 × 7.5 50MHz ÷ 14.4GHz	4.88	2.16

* N: number of turns, R: internal radius (μm), W: metal width (μm), S: spacing (μm)

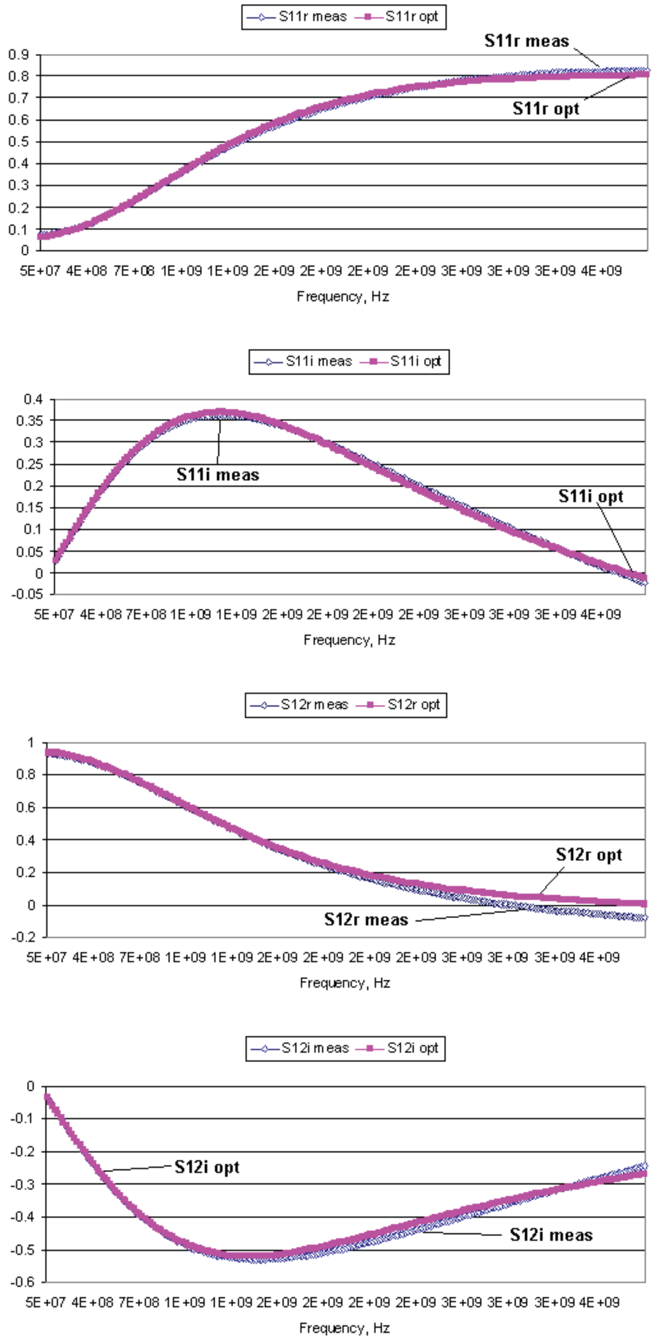

Fig. 7. Comparison between the measured(meas) [10] and GA optimized (opt) real(r) and imaginery(i) parts of the *S*-parameters for 6.5 × 60 × 14.5 × 2 inductor.

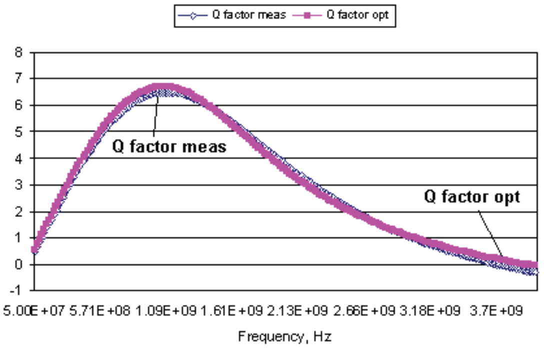

Fig. 8. Comparison between the measured(meas) [10] and GA optimized (opt) Q-factors for $6.5 \times 60 \times 14.5 \times 2$ inductor.

IV. CONCLUSION

A model parameter extraction procedure of planar spiral inductors has been developed. A procedure for direct determination of the model parameters is proposed and realized in the *Cadence PSpice* and *Cadence Probe* environment. The full range error is minimized using a Genetic Algorithm optimization procedure in the MATLAB environment. The presented direct extraction and optimization approaches show very good accuracy in respect to the measured data and can be applied directly in the RF planar inductor design process. The optimization approach based on GA can be applicable for problems, where several independent parameters are optimized in their respective ranges according to predefined purpose function.

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Vladislav P. Durev received the M. Sc. degree in electronics from the Technical University-Sofia, Bulgaria, in 2000 and is currently working toward the Ph.D. degree at TU-Sofia. His research interests include CMOS RF/microwave passive and active device modeling and optimization using Genetic Algorithms.

Ellissaveta D. Gadjeva graduated from the Technical University of Sofia, speciality "Electronics" in 1970. She received PhD degree in the Technical University of Sofia in 1976. Hers field of interest includes CAD in electronics. She is today an Associated Professor at the Department of Electronics, Faculty of Electronic Engineering and Technologies, TU-Sofia.

Marin H. Hristov graduated from the Technical University of Sofia, speciality "Electronics" in 1972. He received PhD degree in the Technical University of Sofia in 1979. His fields of interest include design of semiconductor devices and simulation of integrated circuits, CAD in electronics, computer based architectures, realization of ASIC IC, development of algorithms for computer-aided design of hybrid circuits and printed circuit boards.