

BEHAVIORAL MODELING AND SIMULATION OF SPIRAL INDUCTORS WITH ANSOFT SIMPLORER

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A behavioral model of spiral inductor is developed in the present paper realized using the possibilities of the Ansoft Simplorer simulator. The basic possibilities and advantages of Ansoft Simplorer for behavioral modeling and simulation of electronic circuits are presented. An example is presented illustrating the modeling and simulation of spiral inductors. A comparison of the results with a corresponding PSpice model is given. The designed VHDL-AMS spiral inductor model is simple, algorithmic and realized to be easily implemented as a module in mixed signal simulation of large analog-digital projects.

1. INTRODUCTION

The fast growth of the microelectronic technologies led to complicating the projects and their application in more areas of life. The software for modeling and simulation of electronic circuits and systems faced the challenge with new algorithmic design concepts and module design in the case of very complicated systems. System on Chip (SoC) concept is already widespread, including the design of systems with analog and digital part – mixed signal systems design. This is very important for the marketing strategies of the microelectronic companies, as the module and algorithmic design lead to fast market growth and easy applicable and understandable designs. Separating the projects in modules, described with a behavioral modeling language and the possibility for individual simulation for every module separately and the full system with all modules together is already a general approach for design and simulation of electronic circuits and systems. Because of the fact that VHDL (VHDL-AMS) and Verilog (Verilog-A) are standard behavioral modeling languages, it is easy to use behavioral models for modules of one project for another, which is a big advantage in designing complicated electronic systems. A behavioral model of spiral inductor is developed in the present paper realized using the possibilities of the *Ansoft Simplorer* simulator, based on VHDL-AMS modeling language.

2. GENERAL ADVANTAGES OF ANSOFT SIMPLORER

Ansoft Simplorer is an environment for modeling and simulation of technical systems, which are of different nature – hydraulic, pneumatic, electrical, mechanical etc. The following advantages of the *Ansoft Simplorer* environment are important from the behavioral modeling point of view:

1. Possibility for algorithmic description of the behavioral models using VHDL(VHDL-AMS).
2. Possibility for work with the internal libraries with ready-to-use components as well as possibility to change existing components or to create new components.
3. Possibility for simulation of electronic schematics and systems in time and frequency domains.
4. Possibility for simulation of electronic schematics and systems in s- and z-domains.
5. Possibility for visualization and interpretation of the results as well as making documentation.

Except these possibilities it is possible for *Simplorer* to simulate electronic schematics at different levels – schematic level, system level, mixed signal simulation. The digital blocks can be easily synthesized with a corresponding software for a given architecture (Xilinx, Altera), as they are described in a standard way with VHDL. The analog blocks can be described with VHDL-AMS and their parameters can be determined on the base of a comparison between the behavioral *Simplorer* simulation and the standard *PSpice* simulation of analog models. After the final definition of all schematic parameters of the mixed signal simulation, the system can be analyzed as a whole block, which is in practice a realization of “down-top” approach (Fig. 1).

3. BEHAVIORAL MODELING AND SIMULATION OF SPIRAL INDUCTORS WITH SIMPLORER

The equivalent electrical schematic of a spiral inductor in the Schematic editor of *Simplorer* is given on Fig. 2 [1]. The current source i1 feeds the schematic with 1mA AC current. The parameters of the model, given with the equivalent schematic on fig. 2 are calculated with the following expressions [1]:

$$R_s = \frac{l}{\sigma w \delta (1 - e^{-t/\delta})}; C_s = \frac{\epsilon_{ox} n w^2}{t_{oxM1,M2}}; \delta = \sqrt{\frac{2}{\omega \sigma \mu_0}} \quad (1)$$

$$R_{si} = \frac{2}{G_{sub} l w}; C_{ox} = \frac{\epsilon_{ox} l w}{2 t_{ox}}; C_{si} = \frac{C_{sub} l w}{2} \quad (2)$$

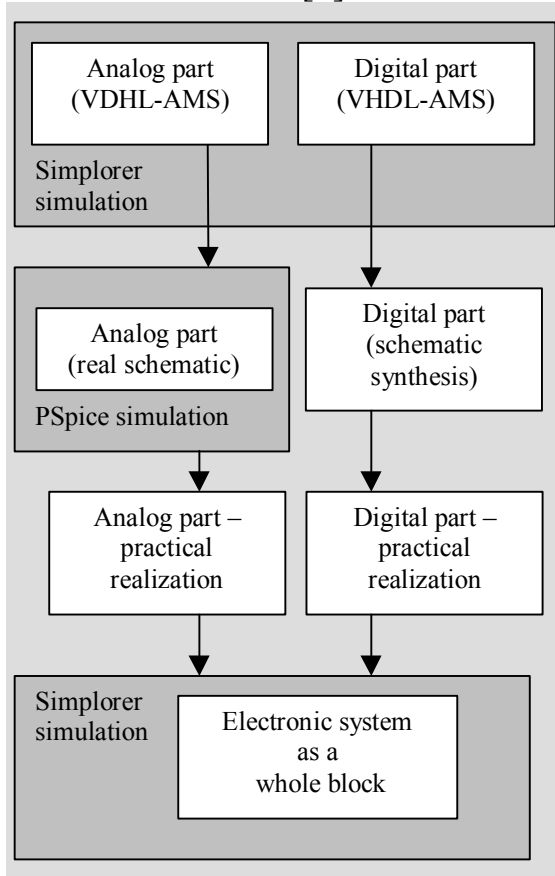
The description of parameters from (1) and (2) is given in Table 1 together with the actual symbols in the *Simplorer* VHDL-AMS model.

Every component from the schematic, given with Fig. 2 is designed as a separated module(entity) with a definite behavior, which is described in the architecture part of the VHDL-AMS model.

3.1 Modeling of the inductance Ls

The inductance Ls of the planar spiral inductors is described using several analytical expressions in dependence on the geometry parameters. The expressions, given [2,3,4] are presented here with the syntax of the behavioral modeling language VHDL-AMS. There are three approximations for the expression, which is used for

modeling the inductance L_s . The first approximation is realized with the modification of the Wheeler formula [2] with K coefficients:



Spiral inductor parameters	Symbol in Simplorer model
Outer diameter D_{out}	D_{out}
Inner diameter D_{in}	D_{in}
Average diameter D_{avg} $D_{avg} = 0.5 (D_{out} + D_{in})$	D_{avg}
Number of turns n	N
Fill ratio ρ $\rho = (D_{out} - D_{in}) / (D_{out} + D_{in})$	R_o
Width of spiral trace w	W
Metal skin depth δ	Δ
Metal thickness	T
Line spacing sp	S_p
Thickness of the oxide insulator between the spiral and underpass t_{M1-M2}	
Thickness of the oxide layer between the spiral and substrate tox	Tox
Inductance L_s	L_s
Metal conductivity σ	Σ
Substrate conductance G_{sub}	G_{sub}
Substrate capacitance C_{sub}	C_{sub}
Length of spiral trace l	L

Fig. 1. Electronic circuits and systems simulation in Simplorer

Table 1

$L_{s_val} == (K1 * mju * ((n ** 2) * D_{avg})) / (1.0 + K2 * ((D_{out} - D_{in}) / (D_{out} + D_{in})))$;
where $K1$ and $K2$ depend on the inductor layout. In the case of square inductors $K1=2.34$ and $K2= 2.75$ [2].

The second approximation is done using current sheet approximation[2, 4]:

$L_{s_val} == 0.5 * mju * (n ** 2) * D_{avg} * c1 * (\log(c2 / ((D_{out} - D_{in}) / (D_{out} + D_{in}))) + c3 * ((D_{out} - D_{in}) / (D_{out} + D_{in})) + c4 * (((D_{out} - D_{in}) / (D_{out} + D_{in})) ** 2))$;
where the coefficients $c1$ to $c4$ depend on the shape of the inductor. In the case of square inductors $c1=1.27$, $c2= 2.07$, $c3= 0.18$ and $c4= 0.13$ [2].

The third approximation is given with the α –coefficients expression[2]:

$L_{s_val} == \beta * ((D_{out} * 1.0e6) ** \alpha1) * ((w * 1.0e6) ** \alpha2) * ((D_{avg} * 1.0e6) ** \alpha3) * (n ** \alpha4) * ((sp * 1.0e6) ** \alpha5) * 1.0e-9$;
where in the case of spiral inductor $\beta=1.62 \times 10^{-3}$, $\alpha1=-1.21$, $\alpha2=-0.147$, $\alpha3=2.4$, $\alpha4=1.78$ and $\alpha5=-0.03$ [2]. The whole expression is multiplied by $1E-9$ in order to obtain the inductance in nH.

The simulation is done for one approximation. The source for another approximations should be commented in the source code of the model.

The whole model of the component Ls follows:

1. Entity part, where the ports of the component and their type are described:

```
ENTITY Ls IS
PORT (TERMINAL Ls1, Ls2 : ELECTRICAL);
END ENTITY Ls;
```

In this case the ports Ls1 and Ls2 are of a type ELECTRICAL and give the connection of the module Ls with the external world.

2. Architecture part, in which the behavior of the module Ls as an electrical component is described:

```
ARCHITECTURE Ls_behav OF Ls IS
QUANTITY V ACROSS I THROUGH Ls1 TO
Ls2;
QUANTITY Ls_val : REAL;
QUANTITY Davg : REAL;
QUANTITY Din : REAL;
CONSTANT Dout : REAL := 0.3611E-3;
CONSTANT K1 : REAL := 2.34;
CONSTANT K2 : REAL := 2.75;
CONSTANT mju : REAL := 1.256E-6;
CONSTANT n : REAL := 2.1387;
CONSTANT w : REAL := 0.2244E-4;
CONSTANT c1 : REAL := 1.27;
CONSTANT c2 : REAL := 2.07;
CONSTANT c3 : REAL := 0.18;
CONSTANT c4 : REAL := 0.13;
CONSTANT beta : REAL := 1.62E-3;
CONSTANT al1 : REAL := -1.21;
CONSTANT al2 : REAL := -0.147;
CONSTANT al3 : REAL := 2.4;
CONSTANT al4 : REAL := 1.78;
CONSTANT al5 : REAL := -0.03;
CONSTANT sp : REAL := 0.1972E-5;
BEGIN
Din == (Dout - 2.0*(n*(sp + w) - sp));
Davg == 0.5*(Dout + Din);
--lapprox
--Ls_val == (K1*mju*((n**2)*Davg))/(1.0 + K2*((Dout - Din)/(Dout +
Din)));
--2approx
--Ls_val == 0.5*mju*(n**2)*Davg*c1*(log(c2/((Dout - Din)/(Dout +
Din))) + c3*((Dout - Din)/(Dout + Din)) + c4*((Dout - Din)/(Dout
+ Din)**2));
--3approx
Ls_val ==
beta*((Dout*1.0e6)**al1)*((w*1.0e6)**al2)*((Davg*1.0e6)**al3)*(n**
al4)*((sp*1.0e6)**al5)*1.0e-9;
IF domain=quiescent_domain USE
I == 0.0; -- Initial condition
ELSE V == Ls_val*I'dot; -- Fundamental equation
END USE;
END ARCHITECTURE Ls_behav;
```

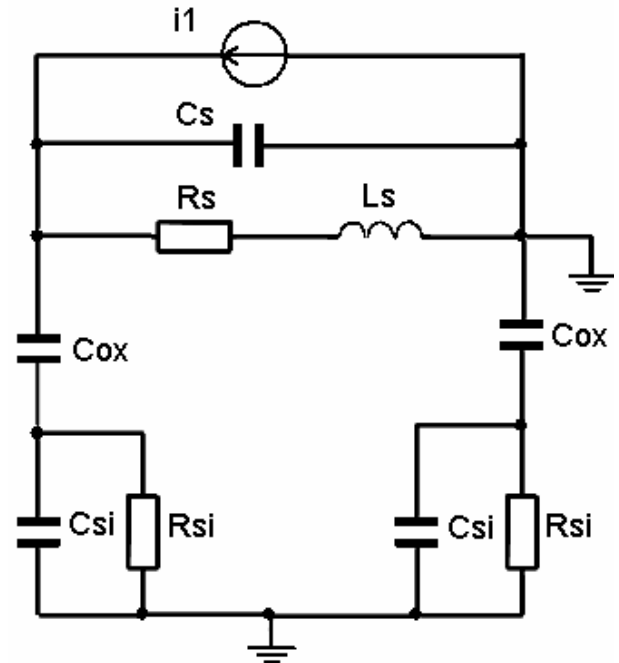


Fig. 2. Equivalent schematic of a spiral inductor

In the beginning of the source all the constants taking part in the model are declared, Din and Davg are calculated and one of the three approximations for the expression, which calculates Ls is applied. In the end the behavior of the inductor is

described with the inductor equation with $I = 0A$ as an initial condition, where I and V are the current and the voltage between the nodes(ports) $Ls1$ and $Ls2$. In analogous way, the rest of the components from fig. 2 are designed.

3.2 Modeling of the resistance R_s

The equation (1) describes the inductor resistance taking into account the skin-effect. The frequency dependence of the resistance R_s can be directly described by the VHDL-AMS language, using the internal variable 'frequency' of the AC simulator of *Simplorer*, which presents the frequency for a given AC analysis step:

$$Rs_val == (L / (w * sigma * (sqrt(2.0 / (math_2_pi * (frequency) * mju * sigma)))) * (1.0 - exp(-t / (sqrt(2.0 / (math_2_pi * (frequency) * mju * sigma))))));$$

Using the user accessible variable 'frequency' simplifies the model of the spiral inductor in comparison with the analogous *PSpice* model, where the frequency of the AC analysis is not directly user accessible[5].

1. Entity part:

```
ENTITY Rs IS
PORT (TERMINAL Rs1, Rs2 : ELECTRICAL);
END ENTITY Rs;
```

2. Architecture part:

```
ARCHITECTURE Rs_behav OF Rs IS
QUANTITY V ACROSS I THROUGH Rs1 TO Rs2;
QUANTITY Rs_val : REAL;
CONSTANT L : REAL := 0.0027;
CONSTANT w : REAL := 0.2244E-4;
CONSTANT sigma : REAL := 3.82E7;
CONSTANT mju : REAL := 1.256E-6;
CONSTANT t : REAL := 5.2356E-7;
BEGIN
Rs_val == (L / (w * sigma * (sqrt(2.0 / (math_2_pi * (frequency)
*mju * sigma)))) * (1.0 - exp(-t / (sqrt(2.0 / (math_2_pi *
(frequency) * mju * sigma))))));
V == I * Rs_val
END ARCHITECTURE Rs_behav;
```

Applying the Ohm's law for R_s (value of the resistor - $V = I \times R_s$) the behavioral model of the frequency dependent resistor R_s is described.

3.3 Modeling of the elements C_s , C_{ox} , C_{si} and R_{si}

The values of the elements C_s , C_{ox} , C_{si} and R_{si} of the equivalent circuit are defined in correspondence with equations (1) and (2), the corresponding representation in VHDL-AMS is:

```
Cs_val == (n * (w**2) * Eox) / toxM1M2;
Cox_val == (0.5 * L * w * Eox) / tox;
Csi_val == 0.5 * L * w * Csub;
Rsi_val == 2.0 / (L * w * Gsub);
```

Modeling the behavior of these components in the VHDL-AMS architecture part is described below:

C_s :

```
IF domain=quiescent domain USE
V == 0.0; -- Initial condition
ELSE I == Cs_val * V'dot; -- Fundamental equation
```

```

END USE;
Cox:
IF domain=quiescent_domain USE
V == 0.0;           -- Initial condition
ELSE I == Cox_val*V'dot; -- Fundamental equation
END USE;
Csi:
IF domain=quiescent_domain USE
V == 0.0;           -- Initial condition
ELSE I == Csi_val*V'dot; -- Fundamental equation
END USE;
Rsi:
V == I*Rsi_val;

```

3.4. Simulation the spiral inductor model from fig.2 in frequency domain:

The simulation of the spiral inductor VHDL-AMS model using *Simplorer* is performed. The frequency dependence of the Q-factor for the three approximation expressions of L_s is presented in Fig. 3. The simulation results are similar with these, presented in [5], where a *PSpice* model of spiral inductor is designed. The results are in a good agreement with the simulated and test results obtained [1,2].

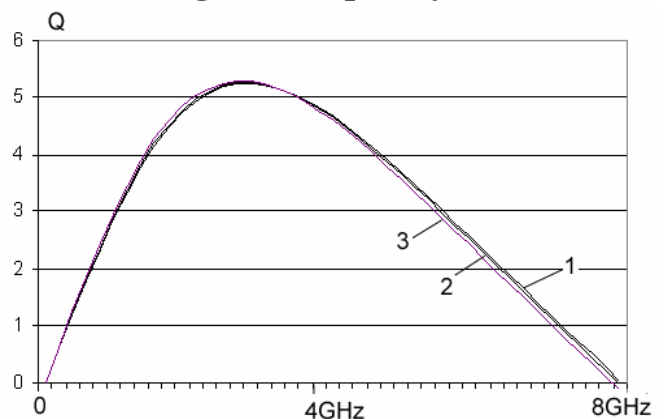


Fig. 3. Frequency dependency of the Q- factor of the spiral inductor

4. CONCLUSIONS

A behavioral VHDL-AMS spiral inductor model has been designed. It is simple, algorithmic and realized to be easily implemented as a module in mixed signal simulation of large analog-digital projects. The simulation results are in a good agreement with the results obtained by *PSpice* simulation and with test results.

5. REFERENCES

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