A Lumped-Element Physical Model for Symmetrical Spiral Inductors and their Mutual Cross-Talk in Silicon RF-ICs

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Abstract - Modern RFICs have achieved an impressively high integration level, making cross-coupling effects among different sections of the circuit a potential limit to their functionality. Integrated spiral inductors occupy a significant chip area and are a potential source of EM interference. This paper investigates the coupling effects between two planar spiral inductors. A physical model for the single inductor is introduced, valid for any kind of excitation (single-ended, differential and also common-mode). The model is then extended to correctly reproduce the coupling behavior under any kind of excitation.

Index Terms - Coupling modeling, cross-talk, spiral inductor, substrate coupling, mutual inductance, skin effect.

I. INTRODUCTION

Increasing the level of integration has been, in the recent past, the main goal in the design of transceivers for wireless applications, leading to compact chips of reduced costs due to reduced bill of materials. On the other hand, a compact solution may determine, especially at high frequency, crosstalk between blocks, worsening circuit performances. Spiral inductors occupy a significant area and are in close proximity one with each other. Electromagnetic coupling among integrated inductors is thus a potential major source of interference. While there are several accurate models for single inductors (which take into account several physical effects, such as skin effect, substrate-induced currents, and current crowding [1]), there is a lack of models to correctly reproduce the coupling between two (or more) inductors on silicon. In this paper we present a model for symmetrical spiral inductors with central tap, able to reproduce their behavior under any kind of excitation. This feature makes the proposed model easily extendable to properly describe the cross-talk between two different inductors.

II. SINGLE INDUCTOR MODEL

Let us consider the symmetric inductor depicted in Figure 1. Usually, this device is connected to the circuit through five nodes, i.e., the coil ends (nodes 1 and 2), the coil center tap (node 3), the bulk (node 4), and the shield (node 5).

Fig.1. 3D view of a symmetric inductor. Nodes 1 and 2 indicate the coil ends, node 3 corresponds to the center tap, node 4 to the bulk and node 5 represents the shield tap.

Figure 2 shows the lumped-element model of a single symmetric inductor, assumed in this paper. Though quite simple, this model has been selected since all its elements are frequency-independent and their values can be easily...
calculated by means of quasi-static simulators such as Ansoft Q3D, or Asitic [2]. We have:

\[
R_s = \lim_{\omega \to 0} \Re(Z_{1,3}) \tag{1}
\]

\[
L_s = \lim_{\omega \to 0} \frac{\Im(Z_{1,3})}{\omega} \tag{2}
\]

\[
M = \lim_{\omega \to 0} \frac{\Im(Z_{1,2})}{2\omega} - L_s \tag{3}
\]

\[
R_{\text{epi}} = \lim_{\omega \to 0} \Re(Z_{1/2/3,4}) \tag{4}
\]

\[
C_{sw} = -\lim_{\omega \to 0} \frac{1}{\omega} \Im(Z_{1/2/3,4}) \tag{5}
\]

\[
R_{\text{shield}} = \lim_{\omega \to 0} \Re(Z_{4,5}) \tag{6}
\]

where \(Z_{m,n}\) denote the impedance seen between nodes \(m\) and \(n\), with the other nodes floating, and \(Z_{1/2/3,4}\) indicates the impedance seen between node 4 and nodes 1,2,3 shorted together. \(R_{\text{skin}}\) is the only term which is deduced from the fitting of the high-frequency response of the inductor, obtained from full-wave simulations.

Note that the symmetry of the inductor is reflected in the model, and that the total inductance is given by the self-inductance of the two coils plus the mutual inductance \(M\). The double-\(\pi\) type scheme obtained in this way correctly models the inductor behavior under both single-ended (i.e., when node 1 or node 2 is shorted to node 5) and differential excitations. This is shown in Figs. 3 and 4 respectively, for the case of a three-turn symmetric inductor with patterned ground shield (diameter = 340 \(\mu\)m, inductance = 4 nH) fabricated in a CMOS065 technology from STMicroelectronics. Model response is compared with measurements (in the case of single-ended excitation) and full-wave simulations from Agilent Momentum, showing a good agreement even above self-resonance. Measurements were de-embedded from pads parasitics by means of a standard open de-embedding procedure [3].

This model also proves accurate when considering a common-mode excitation, when the same signal is applied to node 1 and 2, as shown in Fig. 5, where model response is compared with Momentum simulations. This is useful when it is necessary to evaluate the performance of differential circuit topologies respect to common-mode signals, as in [7].
In all the above simulation we used the value of $R_{\text{skin}}$ deduced by fitting the response in the single-ended excitation. The model response of Fig. 4 and 5 shows that the value of $R_{\text{skin}}$ deduced in a particular configuration remains valid also when considering other excitations.

III. COUPLED INDUCTORS MODEL

The model for two coupled inductors can be obtained by connecting their equivalent circuits by a resistance $R_{\text{sub}}$ and a mutual inductance matrix $[M_{ij}]$, as shown in Fig. 6. Matrix $[M_{ij}]$ models the magnetic couplings between the four halves of the two inductors, while $R_{\text{sub}}$ models the substrate coupling between inductors shields.

$$R_{\text{sub}} = \lim_{\omega \to 0} \text{Re}(Z_{1/2,3/2}^{i,j}) - R_{\text{epi}} - R_{\text{epi}}^{i,j} \quad (7)$$

$$M_{i,j} = \lim_{\omega \to 0} \frac{\text{Im}(Z_{1/2,3/2}^{i,j})}{\omega} \quad (8)$$

where $Z_{1/2,3/2}^{i,j}$ denotes the trans-impedance seen between the ports made by the node pairs $(i',3')$ and $(j'',3'')$, for $i',j''=1,2$.

Although some models have been already presented in literature, they are valid only for single-ended or differential excitation [4-6]. On the contrary, the proposed model allows for correctly reproducing the cross-talk effects under single-ended, differential and mixed excitations of the structure.

This is evidenced by the results reported in Fig. 7 (single ended excitation), 8 (differential excitation) and 9 (mixed excitation), which show the coupling between two identical inductors like the one already considered in the previous examples, separated by a distance of 170 $\mu$m.

The coupling is reported in term of S-parameters of the two-port defined by nodes pairs $(1',2')$ and $(1'',2'')$.

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**Fig. 5.** Momentum simulations of $L$ and $Q$ (black line) vs. model response (grey line), for a common-mode excitation.

**Fig. 6.** Simplified model for a coupled inductors pair.

**Fig. 7.** Momentum simulations of $|S_{21}|$ (black line) vs. model response (grey line) in the case of single-ended excitations.
Fig. 8. Momentum simulations of $|S_{21}|$ (black line) vs. model (grey line) in the case of differential excitations.

Fig. 9. Momentum simulations of $|S_{21}|$ (black line) vs. model response (grey line) in the case of a single-ended excitation on port 1 and a differential excitation on port 2.

For all the examples reported the agreement between Momentum simulations and the model response is good up to about 13 GHz, i.e., three times the self-resonance frequency of the single-ended inductor. Other simulations, not reported for brevity, show that the model is accurate also in the case of pairs of unequal inductors, allowing the simulation of the cross-talk of different integrated blocks.

**IV. CONCLUSIONS**

A lumped element model for symmetrical spiral inductors is presented. This model is derived from the physical characteristics of the structure, and can be simply extended to reproduce the behavior of two coupled inductors, in the case of single-ended, differential and mixed-mode excitations. All the lumped elements are frequency independent and (apart from $R_{skin}$) are straightforwardly obtained by quasi static simulations rather than by numerical fitting of measurements or simulations. Thus the model can be used in simulations both in the frequency and in the time domain.

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