Coupling between inductances in GaAs MMIC design

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ABSTRACT

This paper describes the influence of the coupling between planar spiral inductors on the performances of a monolithic microwave linear circuit behaviour. An equivalent lumped-element model, developed using a full-wave approach, is discussed. The with the foundry model is compared with the standard foundry model. A GaAs MMIC LNA operating in 2.45 Ghz ISM-band is used as a benchmark for validating the model.

1 INTRODUCTION

Computer aided design (CAD) tools are extensively used for the analysis and optimisation of microwave circuits. CADs sometime suffer for poor component modeling, thus, leading to a lack of effectiveness in non-standard situations. The modeling of both active, as well as passive components is receiving a considerable attention in order to extend the applicability of the tools.

In particular, passive structure models are mainly being considered, as they may suffer of a lack of accuracy, owing to unpredicted coupling between the elements. This latter problem is of particular importance in designing MMICs, where a high component density is at a premium and, thus, a strong coupling between closely spaced components may be expected. It is evident that unpredicted effects result in component design failures and, thus, in a cost increase and/or performance degradation. As a consequence, the MMIC designer often has to get the rid of problems which can not be faced using standard component libraries.

Full-wave analysis techniques, e.g. Gupta, Okshi, Jakson are commonly used to gain insights in those cases. Those techniques, while allowing a high degree of accuracy in predicting passive component behaviour, have several drawbacks, mainly due the long computational time required to perform the analysis and to the poor interaction between full-wave programs and commercial microwave CADs. As a consequence, the MMIC designer is discouraged from performing iterative design optimisations.

This paper focuses on the coupling between two closely spaced spiral inductors on a GaAs substrate for establishing in which case such an effect has to be considered and for determining an alternative model to the foundry model.
A couple of spiral inductors have been, firstly, designed according to the GEC-Marconi F20 process layout rules. As a first the two inductors are assume to have the same geometry and orientation, according to Fig. 1 a).

A simple and efficient model of the coupling between the inductances is obtained when a shunt capacitance $C_p$, and a mutual inductance $M$, Fig. 1 b), is added to the inductance foundry model. In this basic form, the model does not separate the different causes of coupling, such as radiative and discontinuity scattering, but it introduces a significant improvement in both linear and non linear analysis.

![Figure 1](image)

The intrinsic equivalent circuit, as supplied by the foundry, is shaped on the well known π-circuit model. The related element values are also supplied by the foundry, whilst the element $M$ and $C_P$ specifically account for the coupling effects due to the close spacing.

The determination of the component values has been approached starting by a 4-port S-matrix description of the coupled spiral inductances, which can be obtained either by measures or by full-wave analysis. The procedure to extract the component values by the S-matrix, starting by a full-wave analysis has been chosen.

Firstly, a proper termination and/or a peculiar interconnection is established for each port, in order to individually extract the model components. For example, making reference to Fig. 1, in order to extract the mutual inductance, a short-circuit termination for port 3 and 4 is required, being the other two ports shorted together.

Using the previously defined termination, a full-wave analysis and a symbolic circuit description are performed. In order to extract the element values, the S-matrix obtained by the full-wave analysis if first transformed in a Y-matrix and then compared with the result of the symbolic analysis.

The above procedure leads to the equations (1) and (2).
where:

\[ M = \frac{2}{j\omega(Y - 2j\omega(C_1 + C_2))} \]  

(1)

\[ Y_{11}^{(4\text{ports})} = \begin{bmatrix} j C_P \end{bmatrix} Y_{11}^{(2\text{ports})} \]  

(2)

is the \( Y \)-matrix with the ports 1 and 4 shorted together and the port 2 and 3 grounded. \( Y_{11}^{(2\text{ports})} \) and \( Y_{11}^{(4\text{ports})} \) are the \( Y \)-matrixes of the isolated spiral inductor and of the coupled structure, respectively.

The results of the above analysis are reported in Figures 2 and 3 for the most common cases.

Figure 2 : Mutual inductance \( M \) versus spacing and number of turn

A number of turns varying between 2 and 9 is considered, although number of turns in excess to 6 is unusual, due to the low resonant frequency of the resulting inductor.

A spacing in the range 12–252\( \mu \)m has been considered. Increasing the spacing above that upper limit leads to negligible coupling effects, while decreasing the spacing below that lower limit is not allowed by the F-20 process design rules.
The above analysis is only valid when two symmetrical spiral inductors of the same size are considered.

An interesting and very common case, however, is represented by a non-symmetrical couple of spiral inductors. With reference to Fig. 1, two inductors, \( L_j \) and \( L_i (L_j < L_i) \), of different size are considered. The same conductor widths and spacings are assumed for both inductors, thus resulting in a different number of turns.

The previously described procedure can be generalised by introducing proper correction factors, \( K_i \). Equation (4) expresses the mutual inductance, \( M_{ij} \), and the shunt capacitance, \( C_{ij} \), in the asymmetrical case, as a function of \( M_i \) and \( C_{ij} \), of the symmetrical case, being \( L_i \) the common value of inductance for that symmetrical case:

\[
M_i = K_i \frac{M_{ij}}{M_i} \\
C_{ij} = K_i \frac{C_{ij}}{C_i}
\] (4)

A simple and efficient way to define this correction factor can be easily related to the size ratio of the two inductors:

\[
K_i = \frac{\text{size}(L_j)}{\text{size}(L_i)}
\] (5)

3 Model Validation

The influence of the mutual coupling between inductors in MMIC design has been evaluated in a simple linear design. A 2.45 GHz ISM band LNA has been
designed, according to the GEC-Marconi F20 process rules and using foundry models. The measured scattering parameters have been compared with the results of a frequency domain simulation brought-out using the foundry model and the corrected model of Fig. 1. In the layout of the amplifier circuit the spiral inductances are extensively used to design the matching networks and the bias feed elements. In order to save chip area, two spiral inductors of the matching circuits are placed at a distance of 60 μm. With the notation adopted above, the values are: \( L_i = 10.94 \, \text{nH} \), \( L_j = 4.98 \, \text{nH} \), \( M_{ij} = 0.4 \, \text{nH} \), \( C_{ij}^p = 10.65 \, \text{fF} \), \( K_{ij} = 0.576 \).

Fig. 4 shows the result of the ISM-band LNA, compared to two different simulations. The first, refereed to as ‘Foundry model’, was brought-out using the standard foundry model. The second, referred to as ‘Corrected model’, takes in account the coupling using the previously described model.

Inspection of Figure 4, immediately shows the improvement in the LNA modeling, due to the proposed model. A gain misfit lower than 1%, is observed using our model, compared to almost 10% misfit obtained using foundry model.

![Figure 4: Measured Vs Simulated results; Corrected model: ---, experimental results: ----, Foundry model: - - - - - - - - - -.](image)

**5 Conclusion**

An equivalent circuit model based on a full-wave approach has been presented for the coupling between spiral inductors. The model is valid for symmetrical as well non-symmetrical geometries. Finally, the model has been validated using an LNA design as benchmark, exhibiting an excellent agreement.
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with experimental results.

REFERENCES


