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RESEARCH ARTICLE

MODELING OF INTEGRATED PLANAR INDUCTORS WITH TWO LAYERS OF MAGNETIC MATERIALS

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ABSTRACT

In this paper, our aim is to develop an electrical model of a two-layer inductor made of magnetic materials. The model developed must take into account the magnetic layers properties as a function of frequency. An electromagnetic simulation, by HFSS software, and an optimization calculation allow to develop an electric model for passive component such a planar inductor. In order to validate the developed model, a recalculation from extracted elements (resistances, capacitors and self-inductors) of the admittance parameters Y_{11} and Y_{12} is necessary. Then, a comparison between the recalculated admittances and those obtained by simulation must show a good agreement between these results.

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INTRODUCTION

The miniaturization of electronic components requires using a new manufacturing technology such as planar technology [1]. This technology allows to reduce the component dimensions, as well as the production costs. Thus, in the literature, planar inductors are presented in different shapes (round, square, …) [2]. The objective of this work is to reduce their dimensions but also to improve their characteristics. S. Musunuri and P. L. Chapman [3] have developed and characterized a 10-turns spiral inductor with 1 µm of space between turns, on a CMOS substrate. This inductor is intended to be used in a DC-DC converter in the frequency range of 1 to 100 MHz with an operating frequency of 10 MHz. The study was carried out on a simple structure and the simulated and calculated values from analytical formulas are identical. In the same way, Charles R. Sullivan and Satish Prabhakaran [4] have developed an inductor to use in a low-voltage, high-current DC-DC converter for powering a microprocessor. It is a triangular shaped inductor and composed of a copper conductor surrounded by a magnetic material obtained by reactive sputtering. The manufactured inductor has been characterized up to 100 MHz, and the measurement results obtained are in good agreement with those obtained by simulation. The objective of our work is to model and simulate two-layer inductors of magnetic material. For this purpose, a 3D simulator, HFSS, has been used to simulate the component. In this paper, we will detail the proposed model for two-layer magnetic inductors, as well as the optimization program developed to determine the model parameters by taking into account the permeability of the magnetic material as a function of frequency. The component used for this study is a planar inductor with to magnetic layer as shown in figure 1.

INDUCTOR MODELING

The increasing in frequency of electronic and telecommunications applications imposes the knowledge of the

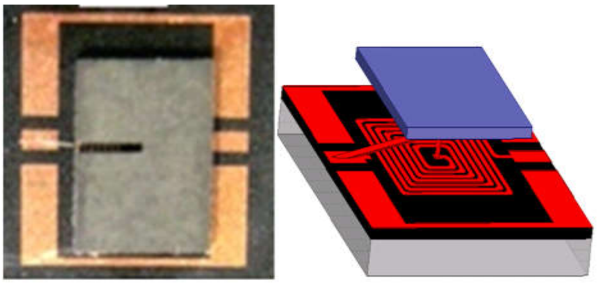

Fig. 1. Planar inductance with two layers of magnetic material

good behavior of numerous elements in the passive component or the integrated circuit. To better take into account the internal phenomena that this component can generate, modeling this latter in a very rigorous way is necessary. Modeling the inductor allows us to identify, with the help of an equivalent diagram, the elements that allow us to take into account its behavior as a function of frequency or when integrated in a circuit. For this purpose, the works of different authors can be classified according to the degree of the model complexity developed, considering losses in the conductors, the capacitive couplings, the influence and the contribution of the magnetic material. First of all, the inductance can be modeled by a self-inductance L in series with a resistor R as shown in figure 2 [5-7].

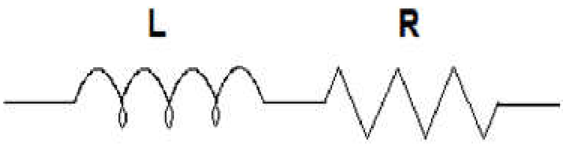

Fig. 2. Simple model

Like the resistance, the value of the inductance L must remain approximately constant up to a limit of the model validity. But the increase its value implies the inadequacy of the model and consequently other phenomena must be taken into account such as the capacitive couplings between turns and properties of the various materials constituting the component [6]. In order to overcome the various drawbacks of the model in figure 2, the authors of [7-8] proposed the model in figure 3 by putting a parallel capacitor with the first model, allowing to take into account the couplings between turns and the couplings between turns and the bonding.

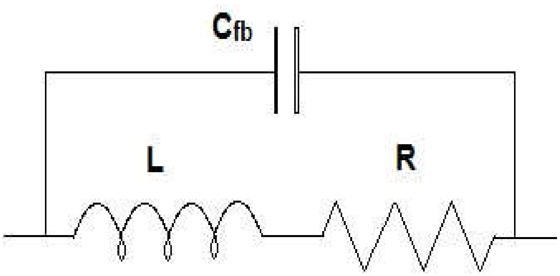

Fig. 3. Model taking into account capacitive coupling

The previous two models do not take into account the effects of the substrate on the inductance characteristics. Thus, the authors of [2], [9-11] and [12] proposed the models in Figure 4 [10] to take into account the parasitic phenomena of the substrate.

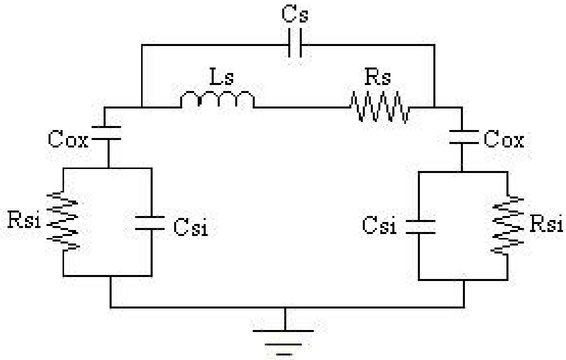

Fig. 4. Model with consideration of substrate effects

DEVELOPED MODEL OF THE INDUCTOR

When a magnetic material is introduced in the fabrication of the inductor, the model becomes more complex. The effect of the relative permeability must be taken into account.

We have chosen to develop a model whose specifications are presented below:

- taking into account the evolution of the magnetic permeability μ_r as a function of frequency, but also the evolution of losses in the magnetic material
- being as simple as possible to size and optimize the component
- taking into account the losses in the conductors (resistance R_{DC}, skin effect and proximity)
- taking into account the capacitive couplings between coils and ground plane and coils.

The model that have been developed is shown in figure 5.

Fig. 5. Develo

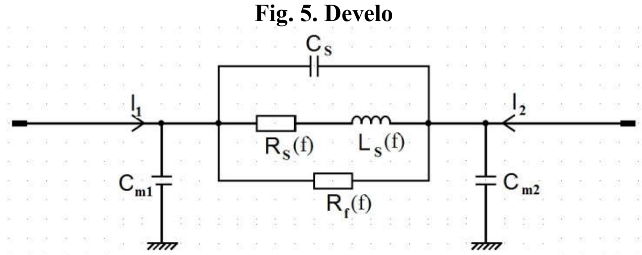

Fig. 5. Developed model

The coil behaviour is represented by an inductance Ls, a series resistance reflecting the Joule losses, a parallel capacitance Cs representing the capacitive couplings, a resistance R_f which allows to take into account the losses due to the eddy current and a capacitance C_m describing the coupling between the last turn and ground plane.

EXTRACTION OF MODEL PARAMETERS

From the simulation results of the equivalent circuit of the model (figure 5), we extract admittance and impedance Y_{11}, Y_{12}, Z_{11} and Z_{12} parameters and then introduce them in the optimization program (figure 6) set up in order to extract the elements of the model, namely the parameters $R_S(f)$, $R_f(f)$, $L_S(f)$, C_S, C_{m1} and C_{m2}.

Afterwards we will recalculate the parameters Y_{11}, Y_{12}, Z_{11} and Z_{12} to validate our results. From the equivalent diagram of the model developed, we obtain:

$$Z_{Sf} = \frac{Z_S * Z_f}{Z_S + Z_f} \quad (1)$$

$$Y_{11} = Y_{C_{ml}} + \frac{1}{Z_{Sf}} \quad (2)$$

$$Y_{12} = -\frac{1}{Z_{Sf}} \quad (3)$$

$$Z_{11} = \frac{Z_{C_{ml}} * (Z + Z_{C_m 2})}{Z_i + Z_{C_{ml}} + Z_{C_m 2}} \quad (4)$$

$$Z_{12} = \frac{Z_{C_{m1}} * Z_{C_m 2}}{Z_i + Z_{C_{m1}} + Z_{C_m 2}} \quad (5)$$

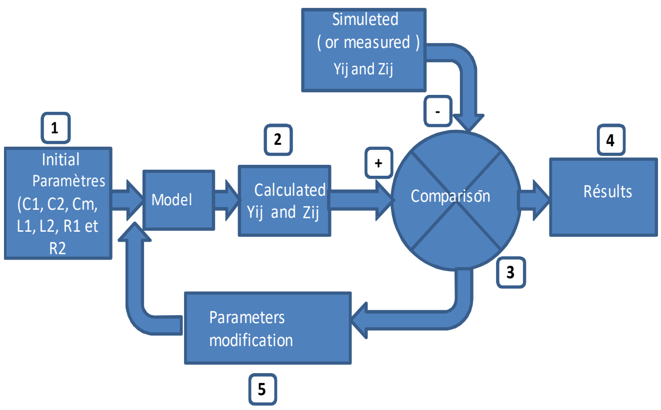

Fig. 6. Optimization program

RESULTS AND DISCUSSIONS

Figure 1 shows the simulated two-layer magnetic inductor, which consists of a copper spiral sandwiched between two layers of magnetic material. We used for the design and study of our component the 3D electromagnetic simulator software called HFSS (High Frequency Structure Simulator). We have simulated an inductor having two layers of magnetic materials with varying relative permeability as a function of frequency as shown in figure 7.

We then extracted the model elements by the optimization program. The constant quantities such as C_S, C_{ml} and C_{m2} are shown in Table 1. The variable quantities such as the resistances R_S and R_f and the inductance L_S are shown in figures 8 and 9.

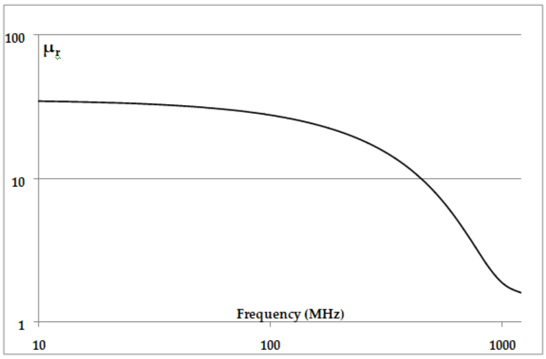

Fig. 7. Evolution of permeability as a function of frequency

Table 1. Capacitor values

C_S (pF)	C_{ml} (pF)	C_{m2} (pF)
0.69	0.3	0.74

Calculation of the inductance: The curve in figure 8 above gives the evolution of the inductance as a function of frequency. We notice in the figure that the inductance follows well the evolution of the magnetic layer relative permeability. In other words, it decreases with increasing frequency and tends to the value of the coreless inductor when the frequency is very large.

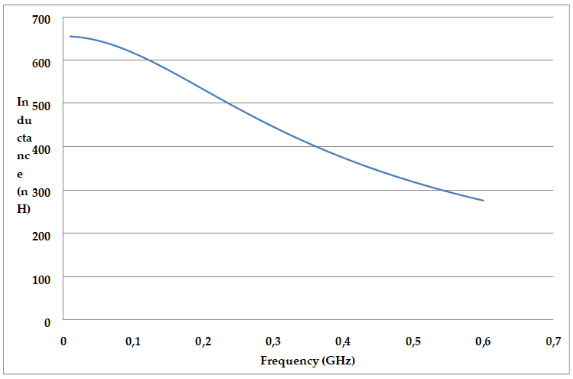

Fig. 8. Evolution of the inductance as a function of the frequency

Calculation of the resistances: The extraction by the optimization program, after simulation, concerns the calculation of the resistance R_S, which tells us that its value increases with the frequency. This increase is mainly due to skin and proximity effects. On the other hand, R_f decreases with the increase of the frequency, this decrease corresponds to the increase of the iron losses in the magnetic material.

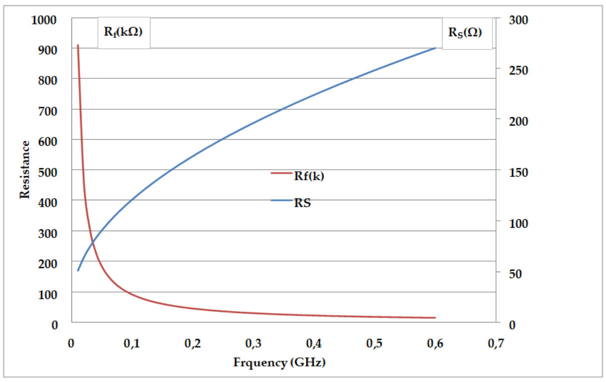

Fig. 9. Resistance as a function of frequency

MODEL VALIDATION

In order to validate our model, we have recalculated from the extracted elements C_S, C_{m1}, C_{m2}, L_S (f), R_S(f) and R_f (f) the admittances Y_{11} and Y_{12} parameters to compare them with the results obtained by HFSS simulation. We note a good agreement between the extraction and the simulation as shown in figure 10.

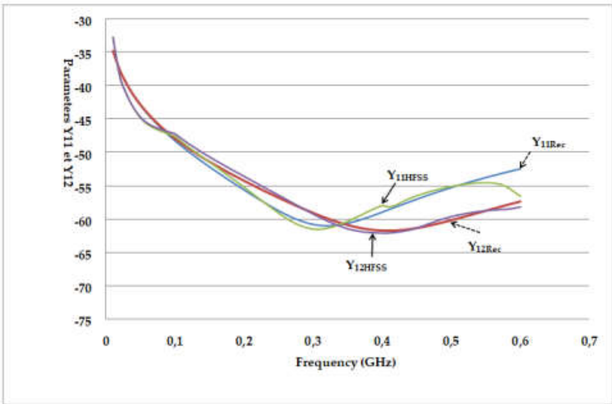

Fig. 10. Comparison of measured and simulated Y_{11} and Y_{12} parameters as a function of frequency

CONCLUSION

An electrical model was developed to take into account the relative permeability (μ_r) of the magnetic material, the capacitive couplings between the turns, between the ground plane and the last turn and the skin effects. Then, an algorithm allowed us to optimize the values of the model from the parameters Zij and Yij simulated by the HFSS software as a function of the frequency. Finally, we obtained a very good agreement between the extracted frequency-dependent parameters and the simulation results.

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