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### RESEARCH ARTICLE

#### MODELING AND OPTIMIZATION OF AN INTEGRATED PLANAR INDUCTOR WITH TWO LAYERS OF MAGNETIC MATERIAL

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#### Abstract

The objective of the work carried out in this document is to develop an electrical model of an inductor with two layers of magnetic material. Simulation and optimization have allowed us to develop a model and in order to validate it, we have realized in the laboratory integrated planar components with two layers of magnetic materials. The different technological steps from copper deposition to the realization of the top layer (in the case of two-layer inductors), through exposure, etching, gilding, lapping, sawing, polishing and bonding have been described (Table 1). These steps required the use of the technological means of the laboratory. From the elements extracted by the optimization program, the admittance parameters  $Y_{11}$  and  $Y_{12}$  were recalculated and compared with those obtained by simulation. We noted a good agreement between the measurement and the simulation.

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#### Introduction:-

Nowadays, electronic trend is to develop new technologies aimed at reducing volume, weight and production cost. Thus, in order to reduce size, occupied space by electronic components and increasing their performance. A magnetic material is very often used to best confine magnetic field in order to increase performance of inductors. The miniaturization of these electronic components (inductors) is necessary by using a new manufacturing technology such as planar technology [1]. Planar inductors come in different shapes: round, square [2].

S. Musunuri and P. L. Chapman [3] have fabricated and characterized a spiral inductor on a CMOS substrate with 10 turns spaced by  $1\mu\text{m}$  of large between turns. This inductor is designed to be used in a DC-DC converter in a frequency range of 1 to 100 MHz with a working frequency of 10 MHz. The study was done on a simple structure and the simulated and calculated values from the analytical formulas are identical. In the same line, the actors Charles R. Sullivan and Satish Prabhakaran [4] have fabricated an inductor for DC-DC converter using to produce a low-voltage and high-current in order to supply a microprocessor. It is a triangular-shaped inductor and consists of a copper conductor surrounded on a magnetic material obtained by reactive sputtering. The fabricated inductor has been characterized up to 100 MHz. Obtained measurement results are in good agreement with those obtained by simulation.

The aim of our work concerns development of models for planar integrated inductors with two layers of magnetic material. Part of the work is carried out using simulation software in order to validate simulation results by characterizing realized devices. A 3D simulator, HFSS, was used to simulate the component.

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In this paper, we detail the proposed model for inductors with two layers of magnetic material. An optimization program was developed to extract the parameters of the developed model. The obtained results using our developed approaches are compared with experimental results.

**Developed model and optimization program:-**

**Developed model:**

The frequency increasing of applications, require to know good behaviour of various elements of passive component or integrated circuit. To take into account internal phenomena that generate latter, it is necessary to model the component rigorously.

Modelling allows us to identify elements using an equivalent diagram. It allows to know component behaviour according to frequency or in a circuit behaviour.

Furthermore, different authors classified works according to degree of complexity of developed model from the simplest to most complex one by considering: losses in conductors, capacitive couplings, influence and magnetic material contribution. First of all, inductor can be modelled by a proper inductance L in series with a resistance R as shown in figure (1) [5-7].

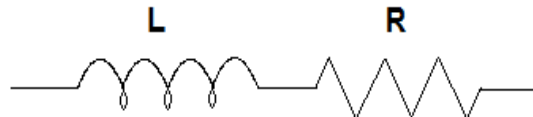


Figure 1:- Simple model.

To resolve different previous model limits, authors [5-10] have proposed model of figure (2). The proposed model takes into account couplings between turns and couplings between turns and bonding.

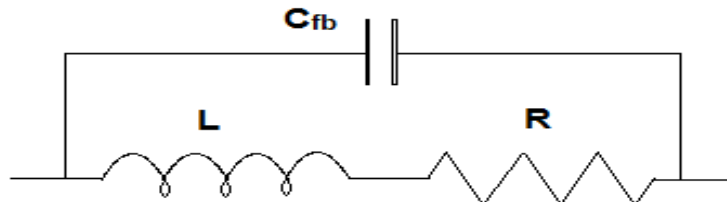


Figure 2:- Model taking into account capacitive coupling.

Modelling allows us to identify elements using presented model in figure 2. When a magnetic material is introduced, the model becomes even more complex. Relative permeability effect of must be taken into account in particular. Thus, we developed the following model that is presented in figure 3.

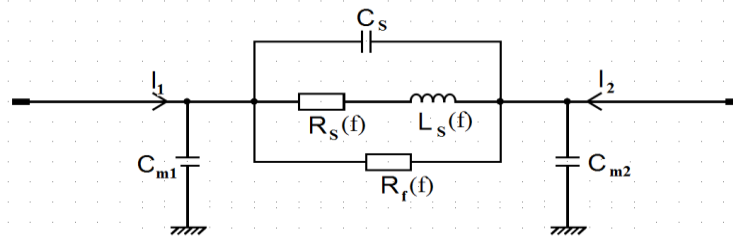


Figure 3:- Developed model.

**Optimisation program for the extraction of model parameters:**

From characterized and simulated results,  $Y_{11}$ ,  $Y_{12}$ ,  $Z_{11}$  and  $Z_{12}$  parameters are extracted to introduce into optimization program. The optimization set-up is presented in figure 4. This program allows to extract model elements named  $R_S(f)$ ,  $R_f(f)$ ,  $L_S(f)$ ,  $C_S$ ,  $C_{m1}$  and  $C_{m2}$  parameters. Then, obtained parameters are compared to validate our results.

Following expressions ((1)-(5)) are obtained from the equivalent diagram model presented in figure 4:

$$Z_{Sf} = \frac{Z_S * Z_f}{Z_S + Z_f} \tag{1}$$

$$Y_{11} = Y_{C_{ml}} + \frac{1}{Z_{sf}} \tag{2}$$

$$Y_{12} = -\frac{1}{Z_{sf}} \tag{3}$$

$$Z_{11} = \frac{Z_{C_{ml}} * (Z + Z_{C_{m2}})}{Z_i + Z_{C_{m1}} + Z_{C_{m2}}} \tag{4}$$

$$Z_{12} = \frac{Z_{C_{m1}} * Z_{C_{m2}}}{Z_i + Z_{C_{m1}} + Z_{C_{m2}}} \tag{5}$$

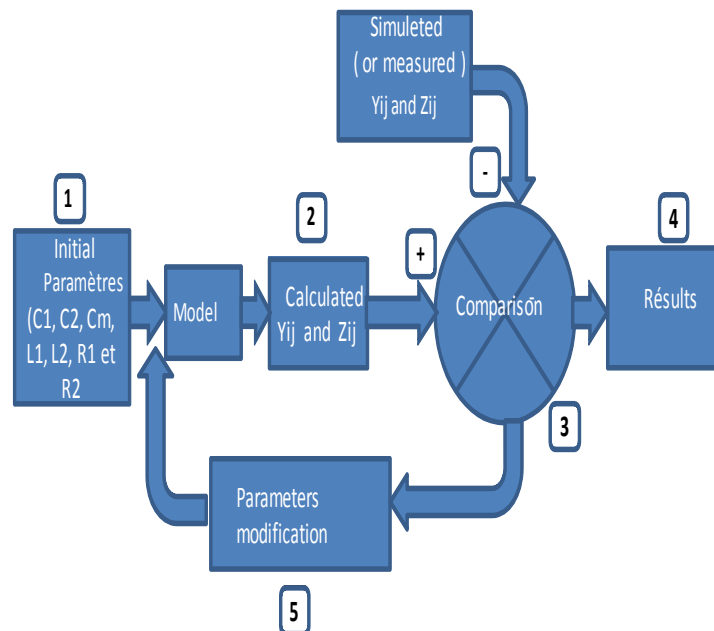


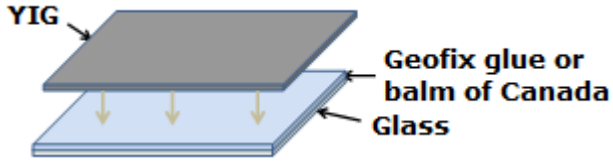
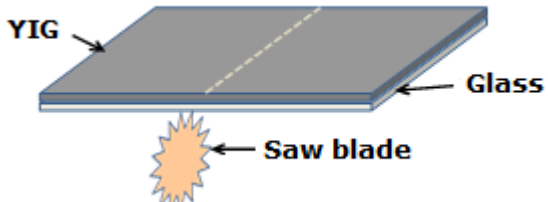


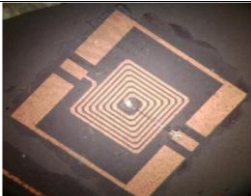
Figure 4:- Optimization program.

**Fabrication of a two magnetic layers inductor:-**

Planar components that are made in our laboratory [11-12] are consist of: one or two thick layers of magnetic materials (from 50 μm to a few hundred μm of thicknesses), a layer of conductive material (classically copper) and a possibly insulating layer (SU8 resin for example). All are being placed on a dielectric substrate (alumina or glass). The substrate is used here as a pure mechanical support. The realization of planar inductors with a layer (thin then thick) of magnetic material (Figure 1) has respectively been the subject of two theses already defended in our laboratory by AdoumKriga in 2008 [11] and DésiréAllassem in 2010 [12].

To fabricate our samples, we used all micro-technological steps. We summarize all our component realization steps in Table 1 below. These steps consist from copper deposition to wires laying connecting the external pad to the internal pad (bonding).

**Table 1:-** Fabrication synthesis of inductors with a layer of magnetic material.

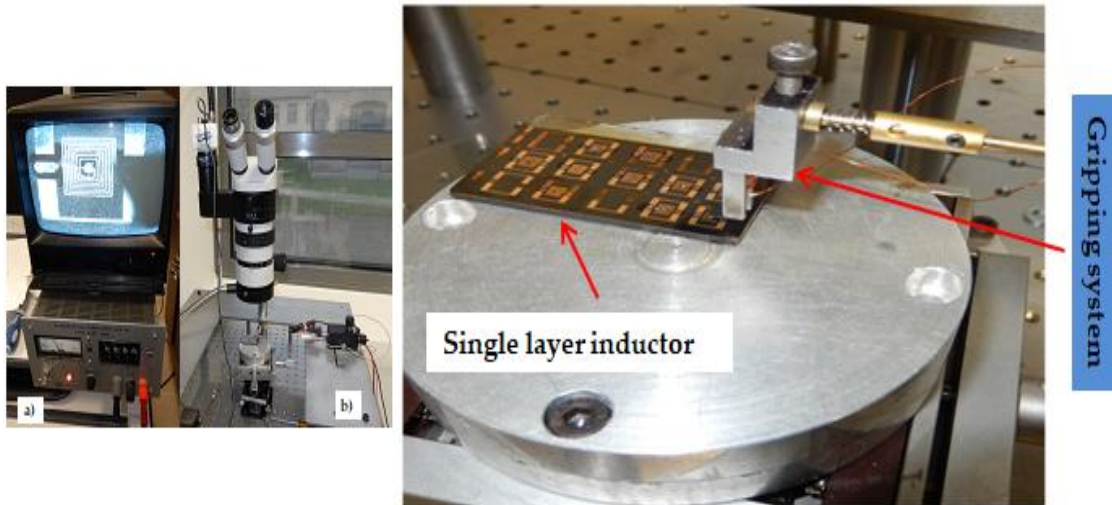
Steps	Photos
<p><b>Bonding of yig substrate to glass substrate (geofix glue)</b></p>	
<p><b>Sawing of the two strips of glued substrates</b></p>	
<p><b>Lapping to obtain the desired magnetic material thickness</b></p>	
<p><b>Polishing for an acceptable surface finish</b></p>	
<p><b>Copper deposition up to the bonding of the single layer inductor</b></p>	

A two-layer planar inductor is an inductor which winding is sandwiched between two layers of magnetic materials. The processes for making this type of inductor are identical to the processes for making inductors with one layer of magnetic material.

In other words, to obtain a two-layer inductor, it is “sufficient” to add a magnetic layer above the one-layer inductor. The realization of such an inductor is very complex because it requires the realization of a connection between the central pad and the external pad while the upper layer is above the spiral.

The bonding of the upper layer is done by using developed bench (figure 5). The bench is composed of: a micro-positioner, a binocular magnifying glass, a viewing screen connected to the binocular, an adjustable plate along the

vertical axis (z axis) and an angle  $\Theta$  and an arm carrying the gripping system (electromagnet). The micro-positioner performs placement operations in a three directions x, y, and z.

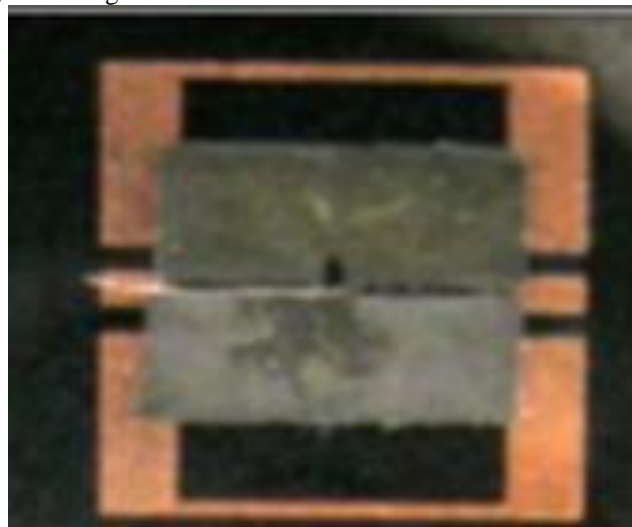


**Figure 5:-** Top layer transfer bench.

Once the system is supplied with a current through the coil, the tip becomes magnetized and allows the upper layer to be taken up. The gripping system presented in figure 5 is attached to the end of the arm of micro-positioner. Its role is to grasp (magnetization) and release (demagnetization) the magnetic plate (upper layer). Via micro-positioner, the upper layer can be moved in three directions in order to position it with precision. Once the layer is well positioned, the current is cut and the layer is released on the target (single-layer inductance).

### Results And Discussions:-

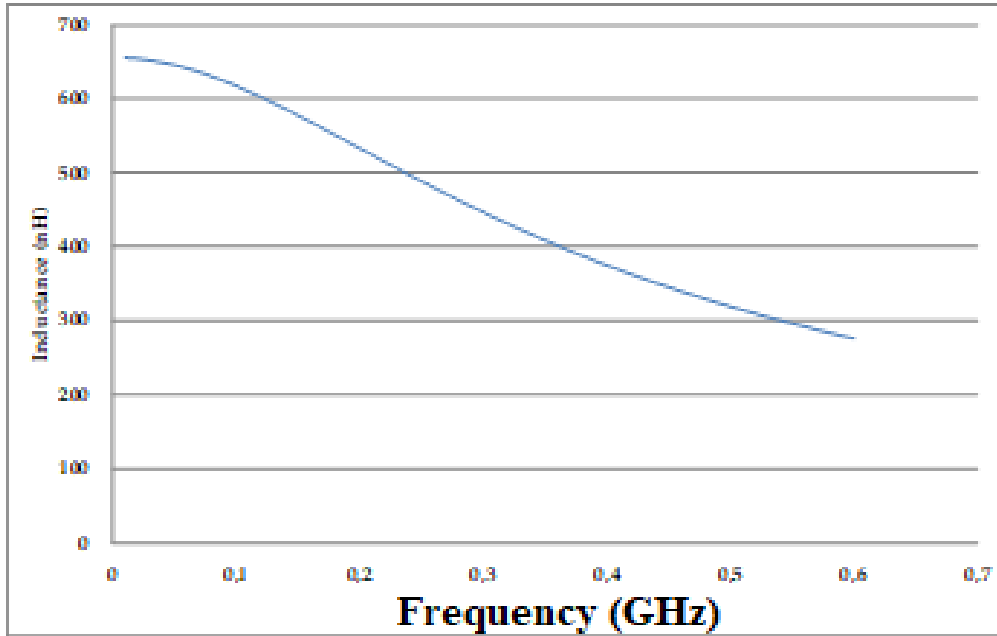
Figure 6 below represents made inductor with two layers of magnetic materials. The latter consists of a copper spiral sandwiched between two layers of magnetic material.



**Figure 6:-**A two-layer inductor with magnetic material.

For simulation part, we have used a 3D simulator, HFSS (High Frequency Structure Simulator). We simulated our inductors with a variable relative permeability as a function of frequency as described in [16].

**Inductance calculation**

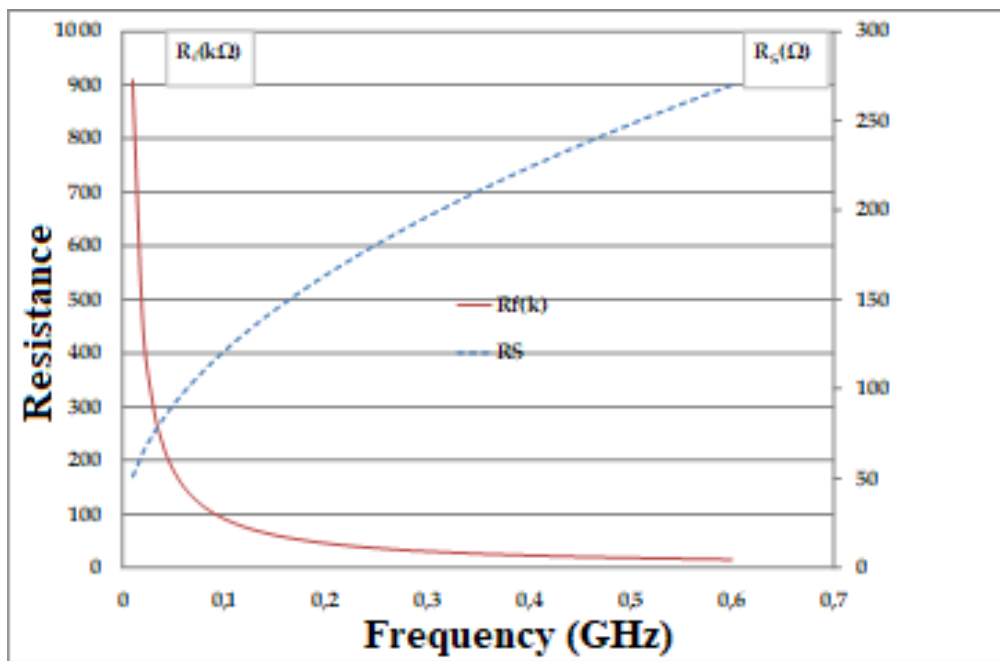


**Figure 7:-** Evolution of the inductance as a function of the frequency.

The presented result in figure 7 above gives evolution of the inductance value according to the frequency. We notice in this curve that the inductance value follows the evolution of relative permeability of the magnetic layer [16]. In other words, it decreases with frequency increasing and tends towards value of air inductance when the frequency is very high.

**Resistance calculation**

The results after extraction by the optimization program indicate that resistance RS value increases with the frequency. This increase is mainly due to skin and proximity effects. On the other hand, Rf decreases with the increase of the frequency, this decrease corresponds to the increase of the losses of Iron in the magnetic material.



**Figure 8:-** Evolution of the resistance as a function of the frequency.

### Validation

Through simulation, inductor with two layers of magnetic materials behaviour has been well studied. The important and sensitive parameters have been identified and obtained. But it is necessary to compare simulation results with those obtained by experimental measurement.

In order to validate our results, we characterized the two-layer components produced and recalculated from extracted elements by the optimization program. The admittance parameters  $Y_{11}$  and  $Y_{12}$  then compared them with the results obtained by simulation. There is a good correlation between measurement and simulation results as shown in Figure 9.

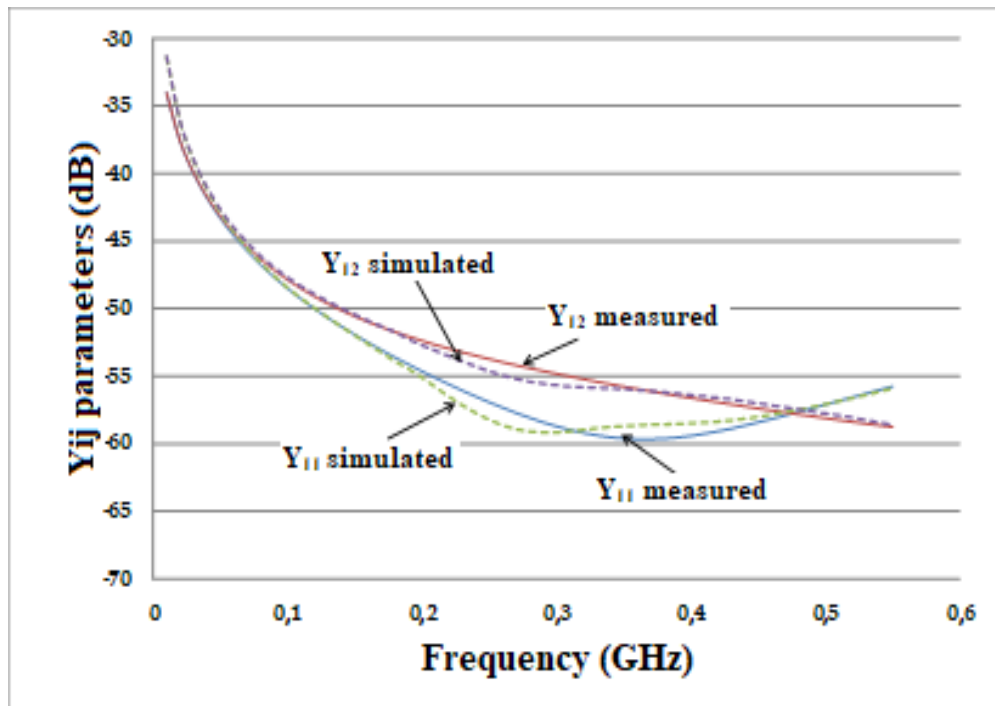


Figure 9:- Comparison of simulated and measured parameters  $Y_{11}$  and  $Y_{12}$  as a function of the frequency.

### Conclusion:-

An electrical model has been developed in order to take into account the relative permeability ( $\mu_r$ ) of the magnetic material, the capacitive couplings between turns, between ground plane and last turn and skin effects.

We developed an algorithm allowed us to optimize model values from  $Z_{ij}$  and  $Y_{ij}$  parameters simulated by HFSS simulator according to the frequency.

Finally, we obtained a very good agreement between extracted parameters depending to the frequency with simulation results.

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