ELECTRIC AND MAGNETIC FEM MODELING STRATEGIES FOR MICRO-INDUCTORS

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***Abstract* — Electroplated micromagnetic components, such as planar and toroidal inductors and transformers with ferromagnetic cores are promising devices. The characteristics of the materials used in these micro-scale components differ significantly from the properties of the common materials used in large-scale magnetics. The dimensional constraints due to the fabrication process form a main difference as well. For the design of such devices, two- and three-dimensional numerical field modeling techniques, such as FEM, are essential. This paper discusses modeling strategies combining two- and three-dimensional FEM methods, along with circuit equations, allowing investigation of the behaviour and design of new components.**

***Index Terms* — Finite element methods, eddy currents, micro-inductors**

I. INTRODUCTION

Integrated micromagnetic components such as planar and toroidal inductors and transformers are a promising new addition to existing technologies. Many applications can be imagined ranging from power or signal transformers to magnetic field sensors to micro-actuators.

Due to the constraints implied by currently available processing techniques, such devices can look and behave quite differently from their macro-world counterparts. First of all, integrated devices are essentially '2.5D' geometries; the thicknesses of the layers are much smaller (~10 μm) than the dimensions in the plane of the substrate (~1 mm) [1,2]. Secondly, the selection of materials that can effectively be used is limited and these materials in general behave far from ideal. Also, they can have highly non-linear characteristics. For example, an often-used magnetic core material is electrodeposited nickel-iron which has a fairly low permeability (~500) compared to thermally treated sheet materials (>10000) [1]. These devices are often expected to operate at frequencies of 1 MHz or higher, where the conductivity of the magnetic material becomes an important factor for the effect of eddy currents.

These limitations imply that well-established design rules for inductive components can not easily, nor effectively be applied to this new class of devices. Therefore, numerical modeling techniques such as FEM become essential tools in development and design optimization. To limit the amount of CPU intensive numerical calculations, a good strategy combining 2D and limited 3D calculations, is imperative.

II. FEM MODELING STRATEGIES

Due to the high intrinsic conductivity and small dimensions (e.g. 100 μm to 1 mm lateral and 10 μm thickness, Fig. 1) of electroplated materials, internal eddy current effects occur throughout the device [2]. The skin depths for a broad operating frequency range of about 10^5-10^6 Hz are of the order of the planar sizes of the devices, and laminations in the vertical or horizontal directions may be required. Especially in plated cores, these eddy currents give rise to flux patterns not occurring in large-scale magnetics. These flux and the eddy current distributions can be studied in 3D-models and 2D-models with external circuits, the so-called '2.5D' modeling [3,4].

A. 3D models

Full 3D-models simulate the most accurate field distribution, but on the other hand are computationally the most expensive. For these types of components, the mesh is easily generated using an extrusion based mesh generator. The number of required elements is a problem since the size of the elements must be related to the skin depth and the

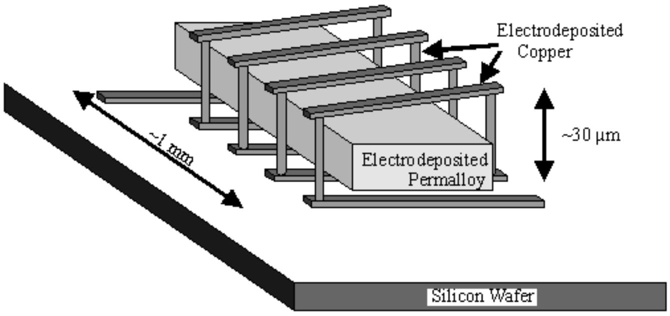

Fig. 1 Schematical representation of micro inductor.

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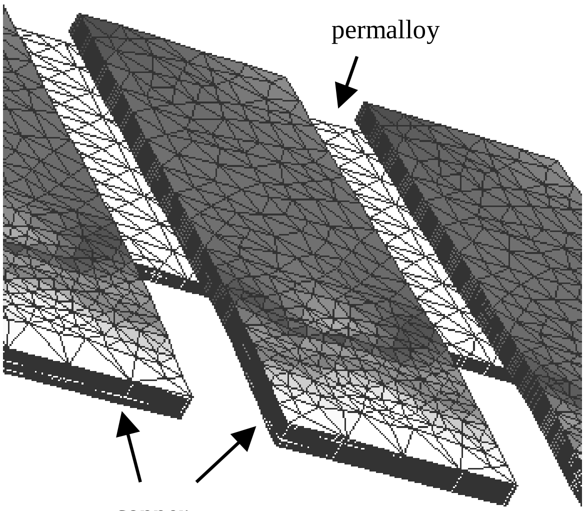


Fig. 2 Current distribution in partial 3D model. Vertical and horizontal symmetry are used to obtain a quarter model. 3 windings are modelled to allow accurate calculation for the central winding, including skin and proximity effects. Darker areas represent higher current densities.

elements have to maintain an acceptable aspect ratio. If necessary, higher order elements can be applied locally, for instance in the core and the conductors. A partial model with appropriate boundary conditions containing a limited number of windings can be used instead of an entire discretization of the complete geometry, e.g. [5].

A similar limited 3D model is used to determine the frequency dependent resistances and (leakage) inductances associated with the parts of the winding situated outside the core plane. These parameters are introduced in the circuit part of the 2.5D model further on. The procedure to determine the parameters is:

1. Build a model with the minimal symmetry properties, considering appropriate cut planes.
2. Insert as many conductors as necessary to obtain a correct proximity effect in at least one (central) conductor.
3. Perform at least 2 simulations with a variable thickness of the core.
4. Determine the (leakage) inductance, for instance by using the magnetic energy obtained in post-processing or by using the voltage or currents if circuit information is available.
5. Determine the resistance by using loss or circuit information.
6. Extrapolate the result to zero thickness to determine the contribution.

The results, obtained using the software package Magnet [6], of a partial 3D model containing three conductors of the central limb of an E-core inductor are shown in Fig. 2. The boundary conditions impose the periodicity of the field. Higher order elements are used in the conducting regions. The skin effects and proximity effects in adjacent conductors are modelled.

B. 2D and 2.5D adaptively generated models

Meshes for 2D models can be generated quickly by means of domain-based problem-specific error estimators and appropriate mesh refinement algorithms. The extension of these models with fully coupled circuit equations containing separately determined lumped parameters leads to '2.5D models'.

The 2D vector potential formulation used in the micro-component analysis includes eddy current and displacement current terms and is given in Eq. (1). The latter is often neglected in the simulation of large scale magnetic devices since it is a minor contribution, but due to the high frequencies applicable in the case of micro-inductors, it may become important. One can note that Eq. (1) is then a special 2D case of the electromagnetic wave equation.

$$\nabla \cdot (\upsilon(A)\nabla A) - j\omega(\sigma + j\omega\varepsilon)A = -(\sigma + j\omega\varepsilon)\nabla V_S \qquad (1)$$

With
υ Magnetic reluctivity
A Magnetic vector potential (def. : $B = \nabla \times A$)
ω Pulsation
σ Electrical conductivity
ε Dielectric permittivity
V_s voltage source

When using the complex conductivity, the field equation can be written under the form of a typical time harmonic equation, that can be solved using slightly altered standard methods [4]. However, in general the displacement current term causes unfavorable numerical properties of the algebraic system to be solved.

$$\nabla \cdot (\upsilon(A)\nabla A) - j\omega\underline{\sigma}A = -\underline{\sigma}\nabla V_S \qquad (2)$$

With $\underline{\sigma}$ Complex conductivity $\underline{\sigma} = (\sigma + j\omega\varepsilon)$

Examination of the interior field by means of 2D field slices of the model of Fig. 2 indicated that 2.5D models are a

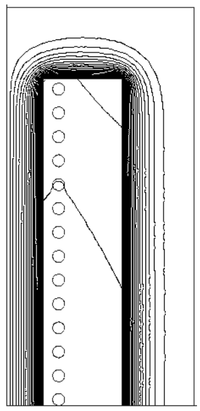


Fig. 3: Flux plot of a 2.5D model (200 kHz). The model is based on a horizontal cross-section of the component presented in Fig. 1.

TABLE I

INDICATION OF THE RELEVANT MATERIAL PROPERTIES

Property	Value
Winding conductivity	5.8 10^7 Sm^{-1}
Core permeability	200
Core conductivity	5.8 10^6 Sm^{-1}

TABLE II

INDICATION OF THE RELEVANT DIMENSIONS

Characteristic	Value
Conductor thickness	5 μm
Core width	180 μm
Core thickness	5 μm
Via diameter	30 μm
Number of windings	28

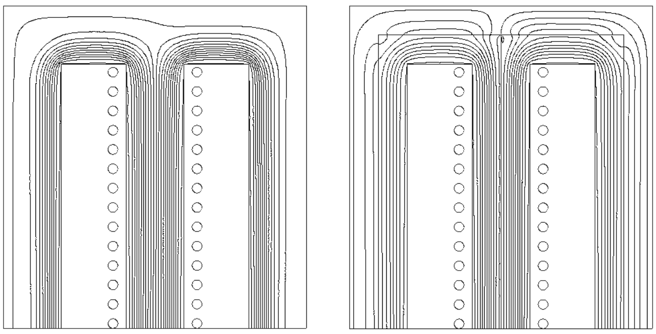
good approximation. The magnetic field lines in a quarter model are plotted in Fig. 3, showing a non-equal flux density distribution due to eddy currents, requiring laminations. The software used for this simulation is the in-house FEM software package "Olympos" [3].

III. APPLICATION: THE EFFECT OF VERTICAL LAMINATIONS

As an application of this approach, the effect of introducing lamination in the model of a micro-inductor with a ferromagnetic core is investigated. A 3D simulation is performed to determine the leakage parameters and the resistance. These parameters are used in the circuit equations. This circuit is connected to the discretized 2D FEM model.

The material properties of the different parts of the device are collected in Table I while the most important dimensions are indicated in Table II. The model contains half of the inductor for reasons of symmetry. Fig. 3 shows the result when no laminations are present. Due to the internal eddy currents, the flux lines are located close to the surface.

In order to obtain a better flux line distribution, laminations may help. Therefore a second model, where the core is split in two parts, is constructed to compare the results. Fig. 4 shows the results of both models, clearly showing the effect of the primitive lamination. The frequency dependence of the inductance value obtained by post-processing is shown in Fig. 5.



(a) (b)

Fig. 4 : Flux lines in a non-laminated and laminated core (10^5 kHz). The model is similar to the one used for Fig. 2.

The strategy to obtain these '2.5D' models described in the previous chapters was applied to a micro-inductor. A detail of the 3D model used to derive the parameters in the circuit equations, can be found in Fig. 2.

IV. CONCLUSION

Different electromagnetic field modeling strategies for small scale magnetic components are presented. Criteria to choose between different strategies are indicated accounting for the presence of internal eddy currents inside the core. This phenomenon does not occur in large-scale magnetic devices, where laminations are standard. The example of a specific electroplated device, simulated using the described strategy, shows the advantageous applicability of 2.5D models.

V. REFERENCES

[1] C.H.Ahn, Y.J.Kim, M.G.Allen, “A Planar Variable Reluctance Magnetic Micromotor with Fully Integrated Stator and Coils,” Journ. Of Micorelectromech. Sys. pp.165-173, vol.2, no.4, December ’93.

[2] H.Ryu, S.Kim, J.Lee, J.Kim, S.Han, H.Kim, C.Ahn, “2D and 3D Simulation of Toroidal Type Thin Film Inductors,” IEEE Trans. on Magn. pp.1360-1362, vol.34, no.4, July ’98.

[3] K.Hameyer, J.Driesen, H.De Gersem, R.Belmans, “Computation of quasi static electromagnetic fields with respect to coupled problems,” 8th int. IGTE symposium on numerical field calculation, Graz, Austria, 21-23.09.98, pp.100-104.

[4] K.J. Binns, P.J. Lawrenson, C.W. Trowbridge, *The Analytical and Numerical Solution of Electric and Magnetic Fields*, John Wiley & Sons, Chichester, Reprint 1994.

[5] O. Dezuari, S.E. Gilbert, E. Belloy, M.A.M. Gijs, "A new hybrid technolog for planar microtransformer fabrication," *Sensors and Actuators*, vol. A71, 1998, pp. 198-207.

[6] *Magnet 5.1 Reference Manual*, Infolytica Corporation, Montreal, 1994.

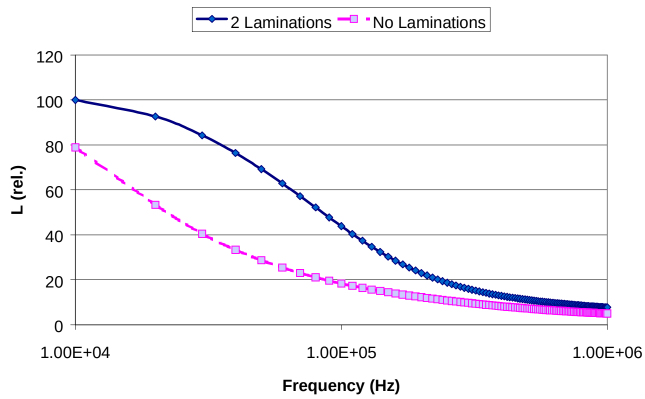


Fig. 5 : Evolution of the inductance value of two inductors, one with and one without laminations.