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To cite this version:

Lamine Ourak, Ayad Ghannam, David Bourrier, Christophe Viallon, Thierry Parra. Solenoidal Transformers for Magnetic Materials Integration. 2012 Asia-Pacific Microwave Conference, Dec 2012, Kaohsiung, Taiwan. p1 - 4, 10.1109/APMC.2012.6421757 . hal-00783047

HAL Id: hal-00783047

https://hal.science/hal-00783047

Submitted on 1 Feb 2013

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Solenoidal Transformers for Magnetic Materials Integration

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***Abstract* — This paper presents the design, fabrication and characterization of suspended solenoidal transformers fabricated using a low cost single step 3D copper electroplating process. The design and optimization of solenoidal transformers with and without magnetic core are performed using HFSS. After optimization, the suspended structures reveal good electrical performance. The addition of a magnetic core to these structures shows a significant improvement of its electrical properties. Thus, an increase of 10% on G_{max}, 20% on coupling coefficient *k*, 80% on the quality factor *Q* and 350% on the inductance is observed. Under probe measurements carried on the suspended structures without magnetic core exhibit a *Gmax* of -1.45 dB and a *Q* of 28.5 at 2.5 GHz. The enhanced performance coupled with the low cost 3D process makes these transformers excellent candidates for today's RF applications.**

***Index Terms* — Above-IC, magnetic core, solenoids, three-dimensional integrated circuits, transformers.**

I. Introduction

Today, RF and microwave applications demands for increased functionality, higher density integration, better passive device performance, reduced footprint and cost are stressing for new enhanced and low cost integration technologies.

Passive components such as transformers are in constant development to enhance their performance and reduce their surface occupation [1]-[2]. Miniaturization, good quality factor *Q* and high maximum available gain G_{max} are the main parameters of transformers that enable their integration in high performance RF circuits. Several approaches have been yet introduced like stacking or narrowing the transformer's inductors, 3D integration in silicon [3] and/or inserting a magnetic material. These approaches suffer mainly from high process complexity/cost and from incompatibility with an above-IC processing.

In this work, we present the development of high performance suspended solenoidal transformers operating at 0.5-15 GHz frequency band and their innovative low cost 3D manufacturing technology [4]. With their reduced footprint, they offer excellent electrical performance since they explore the 3D process to reduce substrate losses [3]-[5]. In addition to their intrinsic performance, these structures offer the possibility of integrating magnetic cores in order to further enhance their performance. The implementation of magnetic materials increases magnetic couplings then increasing inductor values and the *Q* factor. In another hand, keeping constant the inductance values, this implementation allows both the reduction of the occupied area by the component and the *Q* increase.

II. 3D Transformers

A. Design and simulation:

The solenoidal transformers presented in this paper consist of two nested inductors with suspended parts forming a hollow transformer (Fig. 1a). A magnetic core made of dielectric coated FeCo nanoparticles is easily inserted (Fig. 1b).

Transformers are designed and optimized using electromagnetic simulation software HFSS. The simulations are used to tweak the geometry of the structure in order to optimize its performance and take full advantage of the magnetic core while taking into consideration the constrains imposed by the technology.

Fig. 1. 3D HFSS model of the solenoidal transformers: without magnetic core (a), with magnetic core (b).

During the optimization process, we look at the figure of merit G_{max} which is the maximum available when input and output impedances are matched [6]-[7]. G_{max} is calculated using:

$$G_{max} = \left|\frac{S_{21}}{S_{12}}\right|\left(k_s - \sqrt{k_s^{\,2} - 1}\right) \qquad (1)$$

Where,