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Fabrication and characterization of a planar interleaved micro-transformer with magnetic core

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ABSTRACT

This paper presents the design, the fabrication and the characterization of a planar interleaved micro-transformer with an Yttrium Iron Garnet (YIG) core. The design of this micro-transformer and the manufacturing steps are presented. HFSS software is used for the conception and the simulation of the interleaved magnetic micro-transformer. It is composed of two identical windings. A bottom magnetic core is used to improve the integrated transformer performances. To form the windings, we have used a surface micromachining process. We have also used a negative photoresist (SU-8) as an insulating layer and as support for the fabrication of a bridge to connect the central end of the coils to the ground shield. The micro-transformer have been characterized with impedance meter up to 100 MHz, and completed to 1 GHz using vector network analyzer.

1. Introduction

During the last two decades, research has been directed towards the integration and miniaturization of passive components for portable handheld electronics. One of the basic devices widely used in electronics and integrated circuits is the transformer. With the appearance of MEMS technology, many studies were devoted to the integrated micro-transformers for their applications in high frequency domains [1–5].

Recent works addressing both signal and low power micro-transformers are presented:

– The most important application of micro-transformers is DC–DC converters [6–8]. Brunet et al. [6] presented the electrical performances of interleaved micro-transformers. The measured results are compared with predictions obtained from analytical model approach. The use of a micro-transformer in a 2-MHz DC/DC converter was reported in [7,8]. The authors have designed and manufactured integrated HF DC/DC converters using micro-transformers for low-voltage and low-power applications.
– Some micro-transformers are used as gate drivers; they need high insulation for signal and power conversion [9,10]. Half-bridge gate drivers have been widely used in a variety of applications, such as motor drives, power supplies, and plasma display panels. Chen [9] describes a coreless micro-transformer with isolated half-bridge gate driver and an integrated DC/DC converter providing isolated high side supply. In [10] a small-size on-chip transformer-based digital isolator is described in standard CMOS process with a small transformer driving technique to use GHz-band signals.
– Two other studies are dedicated to integrated transformers for signal and energy transfer [11,12]. Wang et al. [11] have manufactured interleaved transformers on silicon substrates to provide isolation for signal and power. They report a very high voltage gain (−1 dB over the frequency range 1–20 MHz). In [12] the authors have reported on coreless planar Printed-Circuit Board (PCB) transformers having high power capability (19 W) and very high power density (24 W/cm^2).
– Micro-transformers are also used in the microwave domain (up to 100 GHz) for telecommunication applications [13,14]. In [13] surface micro-machined RF transformers have been designed, fabricated by using electroplating techniques and characterized. The microwave characteristics of the fabricated micro-inductors and micro-transformers have been measured in the frequency

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range of 0.5–40 GHz. In [14] silicon planar inductors and transformers of spiral shape were designed and characterized on wafer up to 100 GHz. Self-resonance frequencies beyond 100 GHz were obtained.

– Micro-transformers can be also found in recent applications such as hybrid, electric battery monitoring or motor control for electrical vehicles and home automation. In [15] a 6 kV isolated current sensor micro-transformer was designed and characterized from DC to 2 GHz.

Most of the previous studies focus on micro-transformers structures that are compatible with CMOS technology [16]. This means that no magnetic core can be used, while it would permit to increase the performance of the micro-transformer by canalizing the magnetic field lines (low leakage, increase the inductance, and improves the quality factor Q). The use of a magnetic core also permits to reduce the size and the cost of manufacturing [17,18].

Note that a number of studies were devoted to the development of magnetic materials for high frequency applications used in magnetic devices such as in [19,20]. In other works modeling of losses in the magnetic material has been taken in account [21].

This work is based on our previous studies of inductors with magnetic core [22]; the ferrimagnetic core used is a commercial yttrium iron garnet YIG [23]. The interleaved micro-transformer has been designed by using High Frequency Structure Simulation simulator (HFSS) [24].

The frequency behavior of this structure was studied at low and high frequencies using an impedance meter and a vector network analyzer. To manufacture the designed integrated transformer, various techniques have been used: surface micro-machining, RF magnetron sputtering, gold electro-deposition, photolithography in a clean room and finally we have implemented a bridge to connect the central end of the spiral conductors to the external ground shield instead of the classical bonding.

2. Design of the micro-transformer

In the literature three main structures of planar micro-transformer can be found: tapped, stacked and interleaved [25]. The tapped one is suitable for three terminal applications, while the stacked micro-transformer provides the best coupling factor and the highest self-inductance. The interleaved micro-transformer provides lower coupling factor than the stacked structure, but present easier manufacturing process compared to the stacked one. According to this presentation, the interleaved structure is chosen.

Our interleaved micro-transformer is composed of two identical windings with a bottom magnetic layer; the outer coil is the primary and the inner one is the secondary. The square spiral coil is chosen for their advantages compared to the circular and the hexagonal shapes [26]. Fig. 1 presents the chosen design. The micro-transformer has a turn ratio of 10:10, and the size is 10×10 mm^2. The central ends of the primary and secondary spirals of the micro-transformer are connected to the ground shields by using bridges. Table 1 summarizes all the geometrical parameters of the micro-transformer.

2.1. Simulation of the structure

In this section we present the influence of the transformer parameters on the magnetizing inductance. The HFSS simulator is used and two parameters were investigated.

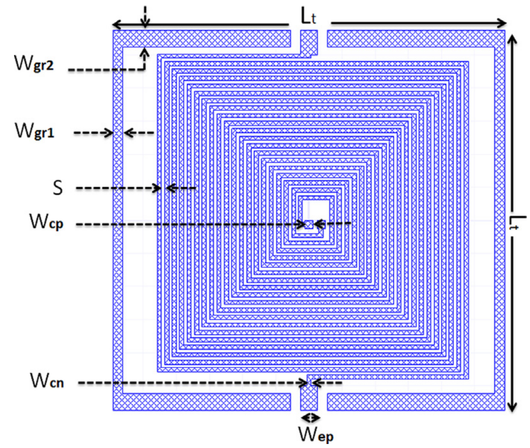

Fig. 1. Mask layout of the micro-transformer.

Table 1
Geometrical parameters of the micro-transformer structure.

Parameter	Designation	Size (μm)
L_t	Total length	10,000
w_{cn}	Conductor width	125
S	Spacing (S)	100
w_{cp}	Central pad width	250
w_{gr1}	Ground width 1	130
w_{gr2}	Ground width 2	500
w_{ep}	External pad width	500

2.1.1. Influence of the magnetic core (YIG)

To observe the influence of the YIG thickness on the magnetizing inductance, we varied the thickness from 0 μm to 300 μm using the transformer parameters listed in Table 1. The results are presented in Fig. 2.

We can see in Fig. 2 that the magnetizing inductance increases with the increasing YIG thickness. Indeed, when the YIG thickness increases, the magnetic fields lines are more concentrated and confined. We also note that the magnetizing inductance is two times higher than the one obtained without any magnetic layer. This result is in good concordance with those found in the literature [27].

2.1.2. Influence of the turn number

In this study the number of turns varied from 1.5 to 9.5 turns. We can observe an increase of the magnetizing inductance with the turn number. This result is in good concordance with those one can obtained with the modified Wheeler formula for air-core inductor presented by [25]

$$L_{mW} = K_1 \mu_0 \frac{n^2 d_{avg}}{1 + K_2 \rho}$$

The same evolution of these two magnetic inductance versus turn number is observed (a constant ratio of 2 is observed between these inductances: the one is without magnetic layer and the second with a 300 μm magnetic layer) (Fig. 3).

2.2. Fabrication process

2.2.1. Fabrication of the coils

Fig. 4 shows the different steps of the interleaved micro-transformer manufacturing with a bridge connection. Commercial YIG plates have been used as a magnetic core to manufacture our micro-transformer [28]. As a copper film will be deposited on the YIG wafer, and to avoid delamination or cracks of this film, the YIG