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Performance analysis of meander-type inductor in silicon and flexible technology

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ABSTRACT

In this paper meander-type inductors are designed and fabricated in silicon and flexible technology in order to investigate the performance of this topology and the possibilities of its utilization in RF applications. The CMOS inductor occupies the area of 0.104 mm^2, whereas the area of the inkjet printed one on flexible substrate is 1693.44 mm^2. In the CMOS case, the inductance is 2.8 nH up to 7 GHz, *Q*-factor is 3.9 at 8.42 GHz and the resonant frequency is at 20.04 GHz. The measured and simulated (ADS Momentum) results differ by as low as 7%. The flexible technology inductor yields inductance of 720 nH up to 30 MHz, *Q*-factor of 2.1 at 50 MHz, while the resonant frequency is at 92 MHz. The design of both components is presented in detail and obtained results are thoroughly discussed in this paper, showing that the meander topology implemented in either of these cutting edge technologies enables wideband inductor operation.

1. Introduction

As integrated circuits (IC) encompass more functionality, many traditionally off-chip components are now built within those ICs. The simultaneous improvement in device technology, miniaturization and ever-increasing number of applications are the driving force of modern engineering. CMOS digital circuits are operating at multi GHz frequencies. Silicon CMOS, bipolar, and SiGe technology have also enabled the operation of cellular phones in the 800 MHz–2 GHz spectrum, and high-speed wireless LAN in the 2–5 GHz bands. Furthermore, for instance, in a modern 130 nm CMOS process circuits are viable up to 60 GHz [1]. Besides these narrow band high frequency (HF) applications, another way to increase the speed of communication is the wideband approach. One example is the ultra-wideband (UWB) standard (covering the spectrum from 3.1 to 10.6 GHz), but a wideband application is generally considered one that uses the band wider than 500 MHz or wider than 20% of the central frequency [2].

Inductors, transformers and transmission lines are used to design matching networks, resonators, filters, etc. As such, they represent the most important components for the design of HF ICs. To create these passive elements, photolithography is used in modern IC processes. Therefore, once properly sized, their characteristics vary little with process and supply voltage [3].

The basic purpose of the inductor is the magnetic field storage within the conductor coils. In contrast to the solenoid type of hybrid component (those fabricated using hybrid IC technologies, such as thin film, thick film or LTCC [4]), due to the limitations of the metal layers in silicon-based technology, on-chip inductors are commonly designed in a spiral shape [5]. Another limitation of CMOS technology is that no magnetic core can be used, whereas it would allow the increased performance by canalizing the magnetic field lines–low leakage, higher inductance and better *Q*-factor [6]. In the case of planar inductors, ohmic loss of metal lines and substrate loss of the conductive substrates represent the obstacle to the improvement of *Q*-factor [7]. Several different approaches to tackling this problem can be found in the literature. For example, in [5], the variations of spiral inductor parameters (metal width and spacing, coil number, inner diameter) are analyzed in order to optimize the performance. Improvement of *Q*-factor by substrate removal is presented in [7]. In [8] several thousands of inductors of different dimensions, parameters and topologies are fabricated, measured and compared with the goal of finding the optimum configuration.

Flexible electronics is a wide-open and rapidly developing field of research and industrial advancement, since it is able to meet the current market requirements for high power density, high operating frequency and low profile of components. Today this technology enables a full spectrum of applications for both industrial (flexible displays and X-ray sensor arrays) and research community (conformally shaped displays and sensors, electronic textiles, active and passive components, such as thin-film transistors (TFTs), capacitors

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and inductors). For example, the mentioned requirements of current technology bring many limitations in using conventional magnetic components, whereas they can be successfully tackled using the components printed on flexible substrate [9]. In [10] flexible-foil PCB is introduced to design an embedded planar transformer in a PCB-assembled power converter, thus significantly reducing the material and manufacturing cost. Thermal simulations for reliability oriented design of planar transformers for high-frequency DC–DC converters are presented in [11]. An important step toward fully inkjet-printed large area and flexible RF systems is achieved by the successful implementation of inductors and capacitors in an all inkjet printed process [12]. In [13] a study on wireless fully inkjet-printed chipless sensor on a flexible laminate is presented.

Meander topology optimization is thoroughly treated in authors' previous work [14–18] and, therefore, is beyond the scope of this paper. The meander topology is specifically chosen for performance analysis within this paper for two reasons. First, it represents a truly planar topology, i.e. it can be implemented without vias. Second, in [19] it was shown that this topology yields the highest coupling coefficient out of several planar variations, i.e. this topology represents a good choice for the design of planar transformers. The motivation for this paper is to investigate the possibilities of meander shape inductors, in the context of RF applications in the wide frequency range. Therefore, two different leading-edge technologies are employed to implement such an inductor: CMOS and flexible substrate. In this way, topology performance analysis is enabled, independent of the fabrication process. Thus, while each of the technologies utilized within this paper comes with its limitations and, thus, results that the same topology implemented in those two technologies is of different e.g. area, length, width and thickness, the characterization results have shown that in both cases some features are in common, such as wideband operation. On the other hand, the characterization process, performed within this paper, shows which of these implementations is more suitable for which of the abundance of RF bands.

To the authors' knowledge, this is the first paper analyzing the same topology implemented in these two cutting edge technologies, thus showing that complementary wide frequency ranges are covered.

In Section 2 through a brief related work review meander topology general characteristics are presented. In Section 3, the design, simulation and characterization of meander-type CMOS inductor are described. The design, fabrication and characterization of an inductor of the same type in flexible substrate technology are presented in Section 4. The obtained results are compared to simulations and discussed in Section 5, and a conclusion follows in Section 6.

2. Meander topology general characteristics

There are multiple ways to implement a planar inductor and those are classified into two-dimensional and three-dimensional structures. Furthermore, each of these categories can be divided into several groups, based on the inductor shape. Thus, two-dimensional structures are either rectangular, hexagonal, octagonal, circular or meander [4]. Types of three-dimensional structures include helical and micromachined solenoid inductors [4], but none of these can be fabricated using either of the two technologies mentioned in Section I, and, consequently, those inductor types are beyond the scope of this paper.

Out of the topologies mentioned within the category of two-dimensional inductor structures, the circular geometry has the best electrical performance. Nevertheless, its layout is very difficult to implement and, therefore, its approximations are used, such as octagonal and rectangular. Of course, utilization of the rectangular geometry is a trade-off, as the layout of it is the easiest to implement but the self-resonance frequency is severely decreased (compared to the ideal circular geometry) [4]. In common for the circular, octagonal, hexagonal and rectangular geometries is that, even though implemented in a technology we dub as planar (CMOS), they are not truly planar. Namely, they all mean that there is a wire spiraling down to a point and, from that point, to make the contact with the rest of the circuit a via needs to be implemented, i.e. at least one more material layer is required.

Even though meander topology provides lower inductance per unit area, it is interesting because it requires only one layer of material to be implemented, i.e. it is truly planar [4]. Consequently, it can easily be implemented in both CMOS and flexible substrate technology. Besides one-layer implementation, its advantage is a significant decrease in eddy current resistance [4]. In [20] an analytical, semiempirical approach has been employed to obtain a partial-element equivalent circuit model (PEEC) and equations relating the geometry layout of the meander type inductors. The model derivation methodology includes measurement of a set of prefabricated meander-type inductors and both analytical and heuristic functions. Finally, the resulting electrical model consists of a lossy inductor (i.e. with a series resistor) in parallel with a lossy capacitor (i.e. with a parallel resistor), Fig. 1. The detailed model development process and exact electrical parameters equations derivation can be found in [20], whereas here only the final equations' form is provided. First of all, the transfer function of the model shown in Fig. 1 is given in the Laplace domain as [20]:

$$Z(s) = \frac{R_C Ls + R_C R_L}{CR_C Ls^2 + \left(L + CR_L R_C\right)s + R_C + R_L}, \tag{1}$$

which can be rewritten as:

$$Z(s) = \frac{s + a_0}{b_2 s^2 + b_1 s + b_0}. \tag{2}$$

The mentioned analytical methods, described in detail in [20], are used to obtain the coefficients a_0, b_0, b_1 and b_2. Once those are determined, the electrical parameters of the model are calculated as [20]:

$$L = \frac{1}{b_0 - a_0\left(b_1 - b_2 a_0\right)}, \tag{3}$$

$$R_L = \frac{a_0}{b_0 - a_0\left(b_1 - b_2 a_0\right)}, \tag{4}$$

$$R_C = \frac{1}{b_1 - b_2 a_0} \quad \text{and} \tag{5}$$

$$C = b_2. \tag{6}$$

The following brief review of related work shows that meander topology inductor implementation can be utilized in a variety of applications and that its investigation represents a developing area of research. In [21] a meander coil is developed and used as a sensor, while in [20] the same topology inductor is printed on PCB to reduce the manufacturing costs and improve the reproducibility of VHF and UHF circuits. The authors in [22] developed the

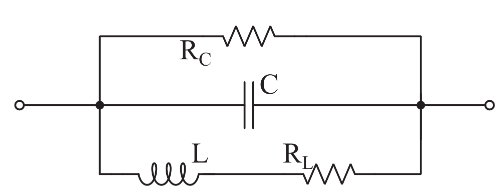

Fig. 1. Meander-type inductor electrical model developed in [20].