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Pseudo-analytical model for calculation of flat circular inductors with rectangular cross-section

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ABSTRACT

This paper proposes a new pseudo-analytical model for calculating dc inductance of flat circular inductors with rectangular cross section. The method developed divides the inductor into a finite number of spirals corresponding with its number of turns. Thus, the total inductance is calculated from the self-inductance of each spiral and the mutual inductance between them. The results were compared with experimental measures carried out in published works. Through 3D simulations made by the Finite Element Method was analyzed how the variation of all geometric parameters of the inductor influences the accuracy of the proposed model. The calculations performed proved to be in excellent agreement with simulations and experimental measurements. Results with smaller errors were obtained when compared to some of classical expressions of inductance calculation in flat circular inductors. In addition calculated inductance is use within an inductor ac equivalent circuit model and compared with 3D simulations.

1. Introduction

The constant technology evolution is associated to reduction of occupied space by electronic components. In this scenario, the use of printed flat inductors on circuit boards represents an advantage over discrete inductors. These components are used in a broad branch of applications, such as RF filters, oscillators, matching impedance circuits and Wireless Power Transfer (WPT) systems. Also, spiral inductors have been widely used as passive components in silicon based integrated circuits. In this application square geometric is preferred than circular, since circular shape is often limited to the availability of fabrication processes, like photolithographic mask generation [1,2]. Besides, inductors on silicon substrate have other limitations. As dimensions decrease, serial resistance of conductors becomes greater. Therefore quality factor of inductor is affected. Another parameter that increases the losses and deteriorates the quality factor is the silicon substrate resistivity. Also, inductance value is limited by parasitic capacitances associated to oxide and substrate.

In Refs. [3–5] are presented inductor simulator circuits that minimize these parasitic limitations. These circuits are based on MOS transistors and a few passive components. The lossless inductor simulators present a quality factor higher than physical inductors fabricated on silicon substrate.

On the other hand, there are applications where physical circular flat inductors are preferred, due to its magnetic characteristics. In wireless sensing applications, for instance, spiral inductors are widely used [6–9].

There are several expressions reported in the literature to calculate dc inductance of flat circular inductors. In Refs. [10–12] simple equations are presented to perform the calculation. They provide reasonable results for typical applications. However, they have limitations for certain geometric conditions. In Ref. [11] an error up to 5% is established for inductors with a radial thickness greater than 20% of the mean radius ($c > 0.2a$). In Ref. [12], the accuracy of the result is compromised when the ratio between turns spacing and conducting track width increases. For both [11], and [12] track thickness is not considered in calculation.

In this work we propose a set of expressions for calculating dc inductance of flat circular coils with rectangular cross section. The results are compared to experimental data and 3D Finite Elements Method (FEM) simulations. Also is studied how changes in all geometric parameters affects the model accuracy. Finally, calculated dc inductance is

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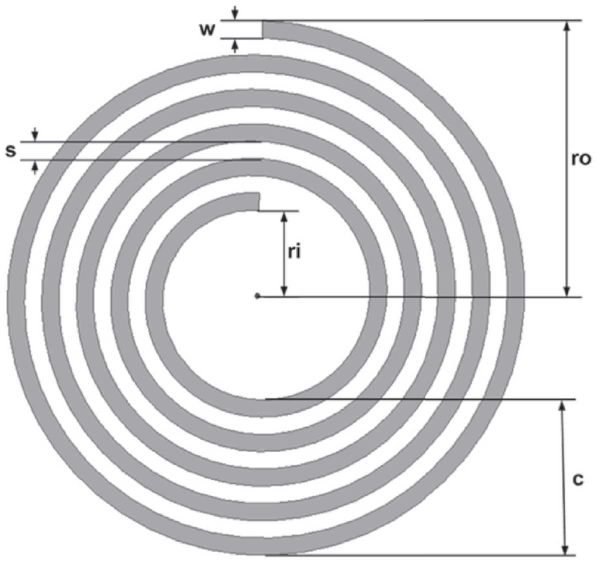

Fig. 1. Flat circular inductor. Main parameters.

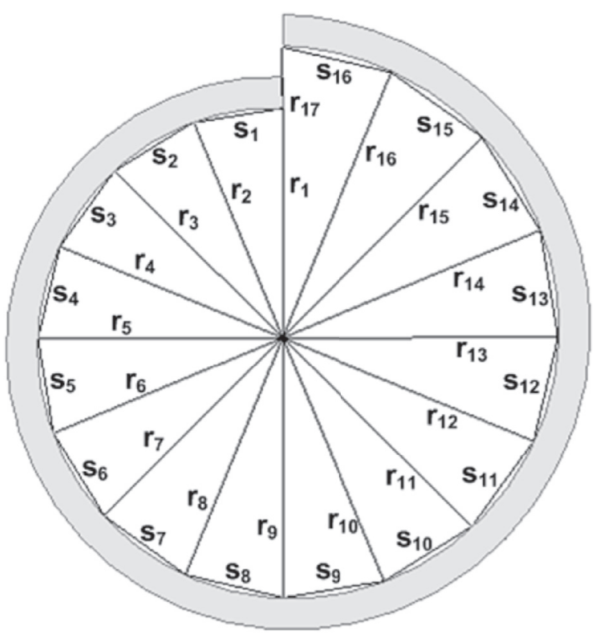

Fig. 2. Single spiral divided into Z = 16 segments.

use within an inductor ac equivalent circuit model and compared with 3D FEM simulations.

2. Used nomenclature

For non ferromagnetic materials, dc inductance depends only on dimensions and geometry of the inductor. In the case of a circular inductor with a rectangular cross section the main parameters are described below:

n: number of turns
ri: inner radius
ro: outer radius
w: turn width
t: conductor thickness
s: turn spacing
a: average radius. (ri + ro)/2

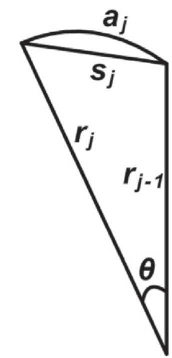

Fig. 3. Triangle formed by two consecutives radii and the segment comprised between them.

c: radial thickness
l: conductor length

3. DC inductance calculation method

Consider a flat inductor as shown in Fig. 1. If it is divided into *n* individual spirals, the total inductance will depend on self-inductance of each spiral and mutual inductance between them, as defined in following expression.

$$L_T = \sum_{i=1}^{n} L_i + 2 \times \left[\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} M_{ij} \right] \tag{1}$$

The method proposed in this work allows calculating the self-inductance of each turn of the inductor and the mutual inductance between them.

3.1. Self-inductance calculation

Each self-inductance depends on length of the spiral. In order to determine this length, each turn can be sectioned in *Z* straight segments. Thereby every segment will have an associated arc of the spiral. This is represented in Fig. 2.

Note that there is an error in considering a segment equal to its corresponding arc. However, it is easy to see how the larger the number of segments, the shorter the length. Thus the length of the arc will be also smaller and will tend to a straight line, reducing the error. The number of segments was set at *360* in this work. It was proved that an amount beyond this value has no significant impact on the results. It is important remark that if the spiral radius increased, it would be necessary to increase the number of segments to keep the error low.

Having *Z* segments we can represent (Z + 1) radii per turn. Here the last radius coincides with the first radius of the next turn. The increment between two consecutive radii is:

$$\Delta r = \frac{w + s}{Z} \tag{2}$$

And

$$r_j = r_{j-1} + \Delta r \tag{3}$$

The length of each segment is calculated from the relation between two successive radii and the angle between them. Consider the triangle in Fig. 3, where r_j *and* r_{j-1} are two consecutives radii and cathetus s_j corresponds with one of the *Z* segments in the spiral. The angle formed between both radii has value $\theta = 360/Z$.

After making some trigonometric manipulations the following expression is obtained for the length of segment s_j.