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Radio-frequency inductor synthesis using evolutionary computation and Gaussian-process surrogate modeling

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ABSTRACT

In recent years, the application of evolutionary computation techniques to electronic circuit design problems, ranging from digital to analog and radiofrequency circuits, has received increasing attention. The level of maturity runs inversely to the complexity of the design task, less complex in digital circuits, higher in analog ones and still higher in radiofrequency circuits. Radiofrequency inductors are key culprits of such complexity. Their key performance parameters are inductance and quality factors, both a function of the frequency. The inductor optimization requires knowledge of such parameters at a few representative frequencies. Most common approaches for optimization-based radiofrequency circuit design use analytical models for the inductors. Although a lot of effort has been devoted to improve the accuracy of such analytical models, errors in inductance and quality factor in the range of 5%–25% are usual and it may go as high as 200% for some device sizes. When the analytical models are used in optimization-based circuit design approaches, these errors lead to suboptimal results, or, worse, to a disastrous non-fulfilment of specifications. Expert inductor designers rely on iterative evaluations with electromagnetic simulators, which, properly configured, are able to yield a highly accurate performance evaluation. Unfortunately, electromagnetic simulations typically take from some tens of seconds to a few hours, hampering their coupling to evolutionary computation algorithms. Therefore, analytical models and electromagnetic simulation represent extreme cases of the accuracy-efficiency trade-off in performance evaluation of radiofrequency inductors. Surrogate modeling strategies arise as promising candidates to improve such trade-off. However, obtaining the necessary accuracy is not that easy as inductance and quality factor at some representative frequencies must be obtained and both performances change abruptly around the self-resonance frequency, which is particular to each device and may be located above or below the frequencies of interest. Both, offline and online training methods will be considered in this work and a new two-step strategy for inductor modeling is proposed that significantly improves the accuracy of offline methods The new strategy is demonstrated and compared for both, single-objective and multi-objective optimization scenarios. Numerous experimental results show that the proposed two-step approach outperforms simpler application strategies of surrogate modelling techniques, getting comparable performances to approaches based on electromagnetic simulation but with orders of magnitude less computational effort.

1. Introduction

Due to the complexity of analog and radio-frequency (RF) integrated circuit design and the demand for short time-to-market, there is a need for robust and efficient automated design methods. The design of an RF subsystem is usually performed by decomposing it into several sub-blocks, which are further decomposed down to the device level. This hierarchical decomposition can be traversed bottom-up or top-down [1]. In top-down hierarchical synthesis, the top level is designed first, resulting in the specifications for the sub-blocks. This process continues down to the lowest level. By the contrary, bottom-up synthesis methods designs the lowest level blocks first, and, then, compose the information of lower level sub-blocks up the hierarchy. Evolutionary computation algorithms may sustain both design methodologies; either through single-objective optimizations (e.g. top-down methods) or multi-objective optimization (e.g. bottom-up methods) [1].

In this paper we will focus on one of the most challenging tasks in RF integrated circuit design: the design of passive devices, e.g., integrated inductors, which are essential components of RF integrated

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circuits [2]. While accurate analytical models are available for active devices to be used in circuit simulators like SpectreRF [3] or HSPICE RF [4], this is not the case for inductors. Typically, designers rely on electromagnetic (EM) simulators, which are the most accurate performance evaluators for these devices. However, EM simulations are computationally intensive. With nowadays' demand for short time-to-market, the usage of iterative EM simulations during the design process is becoming unaffordable; therefore other alternatives must be explored.

In order to reduce the computational effort in the RF design process, designers have developed physical/analytical equivalent models [5–7]. However, these models fail to accurately model the complete useful region of the inductor design space.

In the past few years, surrogate models have been used to replace complex computationally expensive simulation processes by simpler models that can be much more efficiently evaluated [8]. However, these surrogate models still show relatively high errors when trying to model the entire design space.

When these three alternatives for performance evaluation are embedded into an iterative optimization loop for inductor synthesis, different trade-offs between accuracy and efficiency arise. When EM simulation is used, the highest accuracy is achieved at the price of the highest computation time, usually in the range of days. Despite this limitation, they have shown their potentialities especially with multi-objective optimization techniques due to their specification-independent use [9]. Optimization techniques with physical/analytical models for performance evaluation lie at the opposite end of the accuracy-efficiency trade-off: short synthesis times, typically in the range of minutes can be achieved, but with the lowest accuracy, because, generally, equivalent circuit models do not allow an accurate modeling of RF passive components [10].

Such efficiency-accuracy trade-off is significantly improved by the use of surrogate models [11]. However, the difficulties in generating surrogate models that allow an accurate modeling of the entire design space have hampered the development of these approaches. In order to overcome the inaccuracy problem of the previous synthesis strategies, new approaches are being developed based on an initial coarse model, which is locally improved during the optimization process, and have been successfully applied to diverse device and circuit synthesis problems [12–14]. Assuming that the convergence to the global optimum is achieved, the price to pay is higher computational time, as expensive EM simulations must be executed during the optimization process.

In this paper, the different synthesis techniques are discussed and compared for single- and multi-objective optimization of integrated spiral inductors. Then, an intelligent global surrogate modeling methodology is proposed, that is able to predict highly accurate inductor performances over the entire design space and provide comparable results to EM-based synthesis techniques in optimization problems, while enabling the reduction of the synthesis time by several orders of magnitude. In this way, the efficiency-accuracy trade-off for the real world application under exam can be pushed well ahead available methods.

The paper is organized as follows. In Section 2, the inductor synthesis problem is formulated as an optimization problem and the algorithms used in this paper are briefly described. Section 3 overviews the different synthesis techniques reported in the literature, while Section 4 describes the proposed surrogate modeling methodology. This methodology is then used in Section 5 in several single-objective optimization problems, and results for the different surrogate-based synthesis techniques presented in Section 3 are compared. Afterwards, the new surrogate modeling methodology is used for multi-objective inductor optimization and comparisons are made against the same optimizations based on EM simulations. Finally, conclusions are drawn out in Section 6.

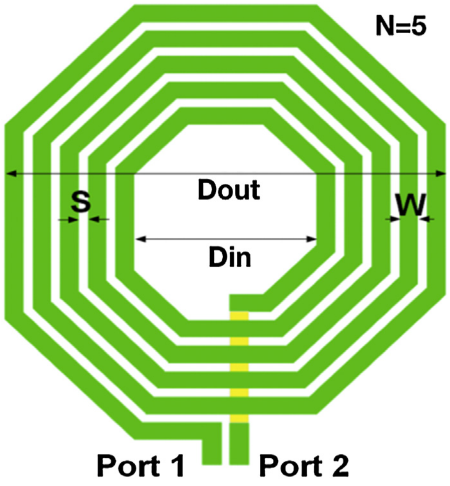

Fig. 1. Inductor geometric parameters for an octagonal asymmetric spiral inductor.

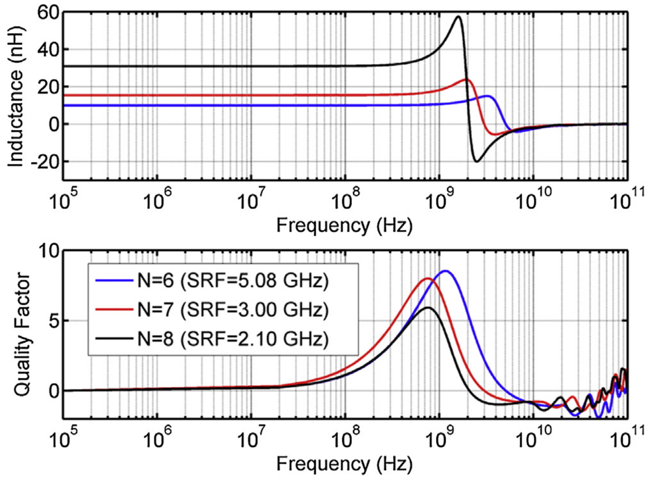

Fig. 2. Illustrating inductance and quality factor as a function of frequency for three different inductors.

2. Problem formulation

Inductors in RF integrated circuits are typically built by using two metal layers (usually the upper ones, to minimize substrate losses) with an intermediate dielectric layer. As illustration's example, Fig. 1 shows the shape of an octagonal asymmetric spiral inductor. The geometry of this planar spiral inductor is usually defined by four geometric parameters: number of turns (N), inner diameter (D_{in}), turn width (w) and spacing between turns (s).

The most relevant inductor performances are the equivalent inductance, L_{eq}, and the quality factor, Q, which are defined as:

$$L_{eq}(f) = \frac{Im[Z_{eq}(f)]}{2\pi f} \tag{1}$$

$$Q(f) = \frac{Im[Z_{eq}(f)]}{Re[Z_{eq}(f)]} \tag{2}$$

where f is the frequency and Z_{eq} is the equivalent input impedance. The equivalent input impedance can be easily obtained from the scattering parameters of the two-port structure representation of the inductor [15].

In Fig. 2, three different plots of the inductance and quality factor as a function of the frequency are illustrated. An important parameter is the self-resonance frequency, *SRF*, which is defined as the frequency at which the imaginary part of Z_{eq} is zero, or, equiva-