Sample Translation

Electronic Engineering

- See below for the original Chinese manuscript.
- **A native-speaker of English who has studied this field** proofreads the translated English.
- The quality of the translated manuscript is suitable for publication in an international journal.

Abstract

In this article, a simplified equivalent circuit in a proposed closed form expression is combined with a triangularity *Q*-curve (quality factor) design methodology (TQ) for spiral inductors to obtain automated optimal design. At first, a closed-form expression is combined with a dual-port equivalent circuit model that contains substrate electromagnetic coupling effect to describe the characteristics for TSMC 0.35 μm process to produce the spiral inductor. The *Q*-curve triangularity characteristic relationship is to verify the accuracy of the model. After comparison of simulated and measured values for S11, the total error and the error for inductance value are lower than 0.71% and 7% respectively. In summary, the enumeration method is used to design all structure to satisfy 1.5 nH and 3.0 nH and obtain the relationship between *Q-curve* peak and triangularity characteristic, which is also used as the condition for optimal spiral inductor. TQ design methodology obtains almost the same optimal structural characteristic as the enumeration method, but only uses half the time. Furthermore, under the restriction of multiple conditions based on physical principles, the design of spiral inductors can approach process limits and optimal performance. TQ methodology will become an effective tool to accomplish SoC (System on a chip) RF IC (radio frequency integrated circuit).

KEYWORDS: Automatic Design, Triangularity, *Q*-factor, Low Frequency Slope, High Frequency Slope, Self Resonant Frequency, RFIC

I. Introduction

While pursuing the wireless communication market development, the use of low-cost and high-performance CMOS (complementary metal oxide semiconductor) technology is the common solution to create system on chip (SoC) technologies [1]. However, the progress of SoC radio frequency (RF) integrated circuits (IC) is dependent on the design efficiency and automation of integrated spiral inductors. In addition, to satisfy the requirement of an accurate inductance value is also a key point for present design.

Spiral inductors are produced on silicon chips to meet the inductance requirement of RF IC. With the assistance of electromagnetic simulation software, the design method [2] needs to calibrate the simulation environment as well as geometrical dimensions to obtain a spiral inductor structure that can meet the circuit requirements. This is a time-consuming and ineffective design method whereby the mass production of a testkey inductor database is established [3]. This not only expensive but also fails to meet circuit requirements. Developing closed form expressions for the physical structure of scalable silicon spiral inductors to find a design method that meets requirements can be divided into two classes: one is the equation developed on geometrical structural dimensions or based on the concepts of electromagnetic physics, using a massive amount of testkeys to obtain empirical formula for curve fitting [4-5]; the other is to use electromagnetic physics-based algorithms [6-9]. Although the empirical formula for curve fitting has a very simple correlation that is suitable for automatic design applications, it has to use a massive amount of curve fitting parameters and therefore it results in insufficient accuracy for calculations. The algorithm proposed by Greenhouse in 1974 has sufficient accuracy and scalability. However, the calculation process is too complicated and not suitable for automatic design.

Abstract

本論文，提出以具體的解析式(closed form expression)的簡化等效電路模型，結合螺旋電感的 *Q* (quality factor)曲線三角形特徵設計方法學(triangularity *Q*-curve design methodology, TQ)，獲致最佳化積體化螺旋電感的自動化設計。首先採用具體的解析式(closed-form expression)結合包含基底電、磁耦合效應的雙埠等效電路模型，描述TSMC 0.35μm製程製作螺旋電感特性，透過*Q*曲線三角形特徵關係驗證模型的準確度，比對模擬與量測在S11的總誤差(total error)與電感值的誤差都分別低於0.71%及7%。綜整以列舉法(enumeration)設計滿足1.5 nH及3.0 nH的所有結構，獲致*Q*曲線頂峰與三角形特徵的特殊關係，並作為最佳化螺旋電感特性的限制條件。TQ設計法獲得最佳化結構特性與列舉法幾乎一樣，但是時間卻少了一倍，同時根據物理為基礎的多目標條件的限制，可使得設計的螺旋電感特性接近製程極限達到最佳化要求。無論如何，TQ法將成為實現單晶片(System on a chip, SoC)射頻積體電路(radio frequency integrated circuit, RFIC)的利器。

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I. Introduction

針對無線通訊市場發展，應用低價的高效能 CMOS (complementary metal oxide semiconductor) 技術，被公認為落實單晶片的解決方案[1]；然而，研發單晶片射頻積體電路的進展速度，受制於積體化螺旋電感(integrated spiral inductor)的設計時效。高品質因子平面螺旋電感的自動化設計開發，對於系統單晶片的發展而言是非常地重要的技術，除了滿足電路需求的準確感值之外；同時，迎合電路應用需求頻段之最佳效能，亦是目前設計的重點之一。

在矽晶片上製作符合射頻積體電路需求感值的螺旋電感，透過電磁模擬軟體協助的設計方式[2]，除了需要校正模擬環境，也必須一再地調校幾何尺寸，以獲致滿足電路需求的螺旋電感結構，將是費時又不具效益的設計方法；藉由大量測試鍵製作以建立電感元件資料庫[3]，除了所費不貲外，同時也無法準確滿足電路之需求；發展可調節的(scalable)矽基螺旋電感的物理結構的具體的解析式，以獲致滿足需求的設計方式，又分類成二大類：一是以幾何結構尺寸或根基於電磁物理觀念所發展的方程式，透過大量測試鍵(testkeys)獲致擬合的(curve fitting)經驗方程式(empirical formula) [4-5]；另一是運用電磁物理為基礎的演算法(physics-based algorithms) [6-9]。雖然擬合的經驗方程式具有非常簡潔的關係式，適合自動設計的應用，但卻必須引用大量擬合參數，肇至計算的準確度不足；而 Greenhouse@1974 提出的演算法雖然準確度及可調節的能力足夠，但計算過程過於複雜，並不適用於自動化設計。