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The development of differential inductors using double air-bridge structure based on integrated passive device technology

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ABSTRACT

Recently, integrated passive devices have become increasingly popular; inductor realization, in particular, offers interesting high performance for RF modules and systems. In this paper, a development of differential inductor fabricated by integrated passive devices technology using a double air-bridge structure is presented. A study of the model development of the differential inductor is first demonstrated. In this model section, a segment box analysis method is applied to provide a clear presentation of the differential inductor. Compared with other work that only shows a brief description of the process, the integrated passive devices process used to fabricate the inductor in this study is elaborated on. Finally, a characterization of differential inductors with different physical layout parameters is illustrated based on inductance and quality factors, which provides a valuable reference for realizing high performance. The proposed work provides a good solution for the design, fabrication and practical application of RF modules and systems.

1. Introduction

Currently, the concept of a system is already deeply stationed in our brains, especially the wireless communication systems that are an indispensable part of our daily life. Many researchers are devoted to studying ways to improve system performance and reduce their size. With regard to the subsystem of a wireless communication system (RF system), it comprises an RF transmitter and RF receiver. Fig. 1 illustrates an overview of an RF transmitter/receiver, which consists of passive devices and active devices on the same chip. It should be noted that spiral inductors are particularly important and widely used in RF transmitter/receiver modules because nearly all devices rely on inductors, such as power dividers, couplers, bandpass filters, mixers, oscillators, and low-noise amplifiers [1–10].

As a key element in RFIC designs, some essential features for spiral inductors include a high quality factor (Q-factor), high self-resonant frequency (SRF), and large inductance range, with small core size, and good models are always attracting researchers' attentions. A high Q-factor is critical, which is important as an index of the contained electromagnetic energies versus dissipated energies, especially in filters, oscillators, and amplifiers. SRF is another critical parameter, which is the upper bound for an inductor to be functional. Both the Q-factor and SRF are major aspects determining the allowed range of application. In addition to the Q-factor and SRF, the inductance has also attracted researchers' attention. The inductors are subjected to realizing large inductance in practice, which leads to an increased circuit size and deteriorated Q-factor. To improve the above-mentioned performance, a group of methods have emerged as required [11–15], and these can be summed up in four categories: trace layout, trace metal parameters, realization of a high resistivity substrate, and use of a substrate shield. In trace layout, the differential circuit topology is the preference; this topology is less susceptible to the supply noise present in on-chip bias lines, offers common-mode rejection, and minimizes even-order mixing products, which can enhance the Q-factor. In the trace metal parameters, the thicker and high conductivity metal layers are implemented because this will reduce the metal line resistance, which leads to the final realization of a high Q-factor. In the use of a high resistivity substrate and substrate shield, some methods, such as a high-resistivity substrate and patterned ground shield, are applied; all of these methods aim to reduce the dielectric substrate loss and radiation loss for the enhancement of the Q-factor. It can be observed that many

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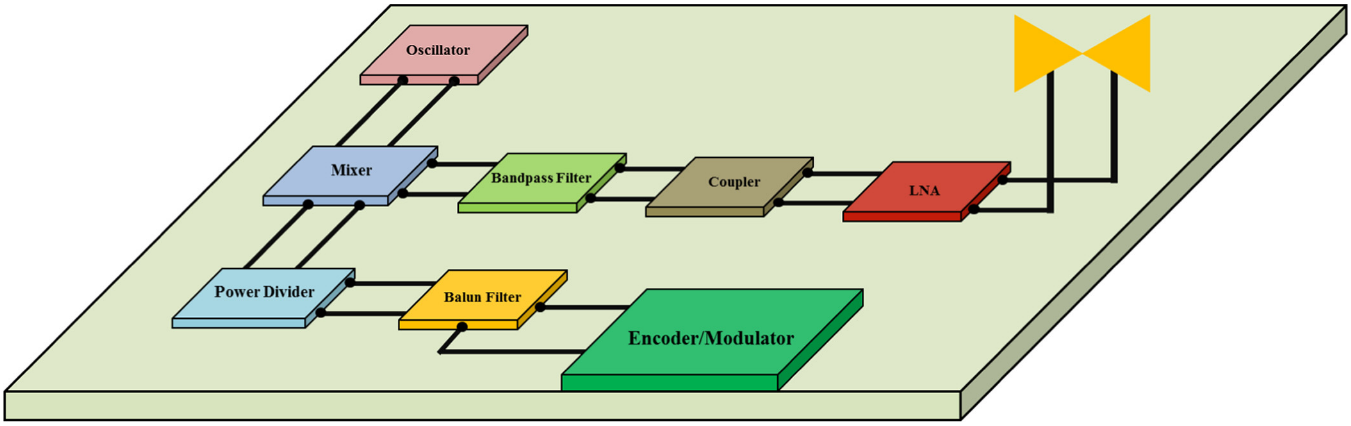

Fig. 1. A diagrammatic sketch of an RF transmitter/receiver.

studies only focus on the improvement of the Q-factor, and little research on the enhancement of inductance has been conducted, except for the use of large ring turns.

However, although many spiral inductor characterizations and models have been presented in these studies [16–18], an accurate differential inductor model and characterization as well as the corresponding fabrication technology are urgently needed but not yet available to the best of our knowledge.

In this paper, a complete set of models, fabrication techniques and characterization resources for differential inductors in the integrated passive device (IPD) process with a three-level metal (double air-bridge) structure is presented. Compared with traditional inductors, the proposed double air-bridge constructed inductor is greatly enlarged per square length, which ensures the realization of larger inductance. In addition, this structured double air-bridge pattern and related fabrication method will illustrate the development of a complicated structure module and system based on IPD process technology. Our presentation includes the following: the proposed structure, model development and the proposed equivalent circuit will first be stated in Section 2. A completed and detailed fabrication flow of the differential inductors with double air-bridge is shown in Section 3. In Section 4, a characterization of differential inductors of the Q-factor and inductance versus varying layout parameters is elaborated, including the number of turns, coil width, coil spacing, inner diameters, ring shapes, metal thicknesses, and substrate thickness. Differing from other studies, all of these analytical characterizations are performed by the measurement-derived data. Finally, conclusions are given in Section 5.

2. Model development of the differential inductor

A 3.5-turn octagonal differential spiral inductor was illustrated in our model development, as shown in Fig. 2(a), but this proposed approach can also be generally applied to other noncircular patterns and other spiral turns. In [19,20], the authors showed that an octagonal spiral inductor can provide a higher Q-factor and lower series resistance than other square patterns and is more area efficient. Actually, the consideration of an octagonal spiral inductor makes the model development more comprehensive compared with other existing square or hexagonal patterns. For such a pattern, the metal track comprises thirteen segments, five one air-bridge overlaps, and two air-bridge overlaps. Fig. 2(b) shows a detailed equivalent circuit for the octagonal differential spiral inductor, and a lumped model representing each segment box is demonstrated in Fig. 2(c). In the modeling process, the capacitive coupling between the metal lines that are parasitically associated with the air-bridge should be considered. All of the components that are used to account for the metal track are shown in Fig. 2(b), where Seg. (x) represents the metal line without overlap, $C_{C,i-j}$ is the coupling capacitance between two named metal lines i and j, and C_{1MM} and C_{2MM} represent the capacitance associated with the first air-bridge structure (between the bottom metal layer and middle metal layer) and second air-bridge structure (between the middle metal layer and top metal layer), respectively. C_{sn_up} and C_{sub_up} represent the capacitances associated with the SiN_x passivation layer and GaAs substrate of the underpass metal, respectively. G_{sub_up} models the substrate conductance of the underpass metal. In fact, there are two types of overlap parasitic components: the first is the one air-bridge overlaps denoted via the subscript 1, corresponding to Fig. 2(a) air-bridge overlap 1 through air-bridge overlap 5; the second is the double air-bridge overlaps denoted via the subscript 2. The introduction of double air-bridge overlaps diminishes the capacitive parasitic effect through the series capacitive effect, which allows for the realization of a higher Q-factor and inductance. The lumped equivalent circuit shown in Fig. 2(c) is the solitary modeled unit present in the conventional modeling of spiral inductors; however, the improved block presented in Fig. 2(b) greatly increases the model accuracy compared with other studies. Because a terminal needs to connect to the adjacent segment box for the coupling capacitive effect, the inductance and resistance are rebuilt into two parts, each with $L_{s/2}$ and $R_{s/2}$. In this study, the modeling of the components in the segment box will first be discussed, and then, the outside segment box components will be modeled.

2.1. Inductance in the segment box

Each metal line is already marked using a number, as shown in Fig. 2(a), which can be further divided into several short straight metal lines. For example, the Seg. 12 metal line can be separated into three short straight metal lines. Therefore, all of the inductance L_{di} of the short straight metal line can be expressed as the summation of the self-inductance L_{si} and mutual inductance L_{mi}. For the total inductance, it is the summation of all of the short straight metal inductances, including L_{si} and L_{mi}, which is written as:

$$L_{di} = \sum \left(L_{si} + \sum L_{mi}\right) \tag{1}$$

In Ji Chen's study [21], a concept of effective linewidth W_{eff} is proposed, so the self-inductance of a short straight metal line can be written as: