High-Q Spiral Inductors with Multilayered Split-Ring Resonator (SRR) Patterned Ground Shields

Abhishek Sahu, Bethany Grayczyk, Mohammad Almalkawi, Vijay Devabhaktuni
EECS Department
The University of Toledo, 2801 W Bancroft St, Toledo, OH 43606
Vijay.Devabhaktuni@utoledo.edu

Peter Aaen
Faculty of Engineering and Physical Sciences
University of Surrey, Guildford, GU2 7XH, UK
p.aaen@surrey.ac.uk

***Abstract*—This paper demonstrates a new concept of multi-layered patterned ground shield (PGS) for improving Q-factor of a Si-based spiral inductor. The impact of left-handed behavior of complementary split ring resonator (CSRR) and split ring resonator (SRR) patterns to realize a high inductance in the ground shield is explained through an equivalent circuit model. The proposed two layer patterned ground shield is shown to improve the Q-value of on-chip spiral inductors by 23.7%.**

I. Introduction

Conventional spiral inductors on Si-based RF IC's have suffered low quality-factor (Q) due to their capacitive and electromagnetic coupling with the substrate at high frequencies [1]. To address this issue, patterned ground shields (PGS) placed beneath the inductor have been widely adopted to suppress electromagnetic coupling resulting in an enhancement of Q-factor and improvement in isolation between the inductor and the substrate [2, 3]. In this paper, we propose the use of CSRRs and SRRs in the design of a two-layer patterned ground shield. We demonstrate that the diamagnetic behavior of CSRRs and SRRs results in an increase of the inductance and the Q-factor. 3D full-wave electromagnetic simulation results demonstrate the significant benefits of the proposed technique.

II. Analysis of Ground Shield

A. Solid Ground Shield

The role of a conductive ground shield located inside the SiO_2 layer is to block the vertical E-field from penetrating into silicon substrate. An image current (due to Lenz's law), also known as loop current, with a direction opposite to that of inductor L_1, is induced on the solid ground shield by the magnetic field of the spiral inductor, in reference to Fig. 1(a) [2]. Such current results in negative mutual inductive coupling between the spiral and the ground shield thereby reducing the overall magnetic field as well as the Q-factor.

B. Proposed CSRR-SRR Ground Shield

To increase inductance and Q-factor, the magnetic field in the structure must be increased. This requires an image current on the ground shield that is in phase with the current in the spiral. A circuit composed of sub-wavelength sized CSRRs and SRRs arranged periodically can behave as if it were a medium with negative constituent parameters and exhibits negative phase and group velocities. Hence, by properly coupling the CSRR and SRR elements with a planar structure through the addition of capacitive gaps, left-handed behavior can be obtained [4]. This concept can be applied to ground shields where the shield can be designed to exhibit a strong diamagnetism in which current is induced opposite to the external magnetic flux as shown in Fig. 2(b). This creates a positive mutual inductance and increased inductance.

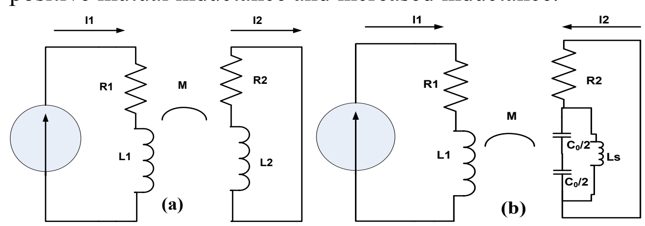

Fig. 1. Equivalent circuit model illustrating the effect of negative and positive mutual coupling in (a) Solid Ground Shield (b) CSRR-SRR patterned ground shield (exhibiting left-handed behavior).

Figure 1(b) depicts the equivalent circuit model for the new ground shield, where the primary and secondary circuits represent the inductor and ground shield respectively. In the secondary circuit, R_2 represents the ground shield resistance and the CSRRs and SRRs are modeled using resonant tanks L_s and C_0.

The induced current in the secondary conductor is in phase with the current in the primary conductor (both in clockwise direction) resulting in a positive electromotive force on the spiral as shown in Fig. 2. This effect can be explained by adding reflected impedance Z_s in series with the primary conductor [2], where

$$Z_s = \frac{\omega M^2}{R_2 + j\omega L_{eqv}}. \quad (1)$$

In (1), M is the mutual inductance and R_2 and L_{eqv} are the resistance and inductance of the ground shield respectively.

Due to the net positive electromotive force imposed by the secondary circuit, net input impedance in the circuit becomes

$$Z_{tot} = R_1 + j\omega L_1 - Z_s. \quad (2)$$

Further, it can be noted from eq. 1 that the imaginary part of Z_s is negative. This signifies the increment in overall inductance of the equivalent circuit. The net resistance in the circuit decreases due to the real part of the Z_s, which implies lesser additional loss due to the proposed two layer ground shield.

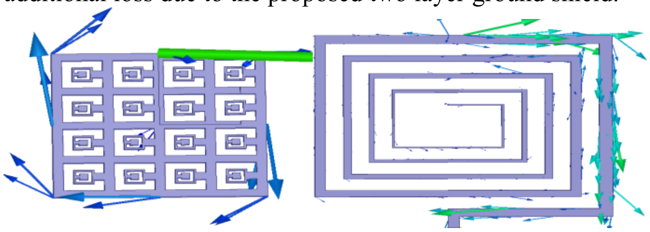

Fig. 2. Simulated surface current vector on the ground shield and inductor showing that the current direction in both is same.

III. DESIGN CONSIDERATIONS

A. Spiral Inductor

Fig. 3(a) shows the top layout of the spiral inductor studied in this research work, which has 3 turns, a spacing of 13 um, an inner dimension of 60 um × 80 um, and an overall area of 200 um ×213.5 um. In order to achieve a high *Q*-factor, we considered both the cases of circular spirals and narrowing line width spirals. 3D full-wave electromagnetic simulations have shown that the narrowing line width spirals achieve a higher *Q* factor [5], because they minimize the effect of eddy current, thereby resulting in uniform current flow both in the inner and outer portion of the inductor. The metal widths from the outer to inner turns are 8.5 um, 7.5 um, 5.5 um, 3.5 um, and 1.5 um respectively. A 0.5 um thick underpass is used to connect the center of the spiral inductor to the outer layer. The proposed inductors are fabricated on a silicon substrate with a width of 290 um and a resistivity of 10 Ωcm. The substrate and ground shield are separated with a 10 um thick silicon dioxide layer.

B. SRR and CSRR Patterns on Two Layer Ground Shields

Fig. 3(b) and 3(c) depict the two layers of patterned ground shield. The first layer is a CSRR patterned ground shield and the layer beneath is the second SRR patterned ground shield. Each layer is formed by a poly-silicon layer of 0.3 um thickness and a resistance of 15Ω/sq. Both the layers are separated with a gap of 4 um.

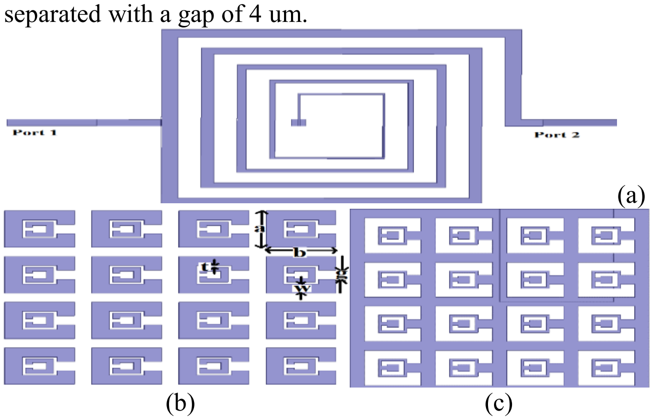

Fig. 3. (a) Layout of the spiral inductor with two ports (turns=3, inner dimension=60um×80um, overall dimension= 200um×213.5um) (b) First layer CSRR ground shield (c) Second layer SRR ground shield (*a*=4um, *b*=4um *g*=1um, *w*=1um, and *t*=0.3um).

The two layers are arranged in such a manner that when looked from above it appears as a solid ground shield. The entire structure is designed and simulated using Ansys *HFSS* finite-element based full-wave electromagnetic simulator.

IV. RESULTS

Fig. 4 shows the simulated *Q* factor characteristics for port 1 (Q_1) versus frequency of the spiral inductors without and with the proposed two layer ground shield. It can be seen that, inductors with the proposed two layer ground shield achieve a 23.7% increase (from 29.6 to 36.7) in Q_1 at 3.4 GHz when compared to spiral inductors without ground shield. The same trend is observed for port two where the increment was found to be 21.3% (from 27.6 to 33.6) at 2.8 GHz. Simulated results show that the effect of the proposed two-layer ground shield on inductance is almost constant with frequency.

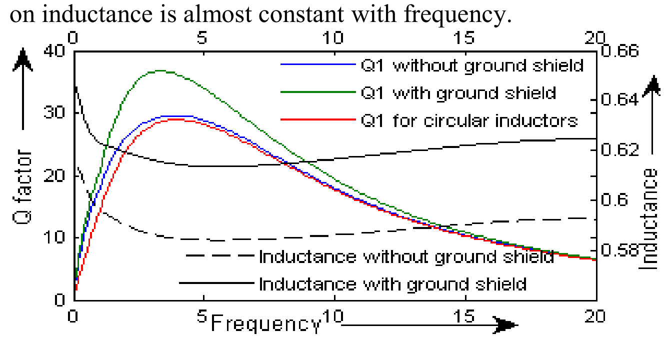

Fig. 4. Simulated *Q* factors of the inductors at port 1 (i.e.Q_1) with and without the two layer ground shield.

V. CONCLUSION

The concept of double layered ground shields employing artificial periodic patterns (i.e. CSRR and SRR) is proposed for improving the *Q*-factor of Si-based spiral inductors. The left-handed behavior of CSRRs and SRRs for enhancing the inductance has been analyzed with the aid of a circuit model. Simulation results confirmed the enhanced performance of spiral inductors with the proposed two layer ground pattern, when compared to spiral inductors without such ground shield.

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