

A Fundamental Approach for Design and Optimization of a Spiral Inductor

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Abstract: This technical paper presents a fundamental approach for design and optimization of a spiral inductor using ASITIC (analysis and simulation of spiral inductors and transformers for ICs) and SpiralCalc (integrated spiral inductor calculator). Both tools are available for research and non-commercial purposes. Inductors are key components esp. for impedance matching and are designed such that they would exhibit a high Q-factor (quality-factor) for the specific inductance and frequency range of operation. A sample value of 5.3 nH is set for this paper for the spiral inductor design using the tools. For optimum Q-factor, an octagonal geometry for spiral inductor is used for ASITIC design, to have a close comparison to that of the SpiralCalc. Design methodologies for the optimization of the spiral inductor parameters such as the inductance and the Q-factor are discussed. Results comparison between the two tools is also presented. Design tradeoffs between inductor parameters are inevitable, and these parameters affect the performance of the inductor esp. at higher frequencies. With this, it is crucial that inductors be designed carefully for their effective frequency range of operation and specific requirements of the intended application.

Key words: Spiral inductor, Q-factor, inductance.

1. Introduction

Monolithic implementation of on-chip passive components of RFIC (radio frequency integrated circuit) has become highly preferred by designers and researchers as it provides high level of integration with cost, area, and power savings [1]. These passive components such as resistors, inductors, and capacitors, should be carefully designed and if possible have characteristics and performance close to ideal to satisfy the high quality and high performance requirements. Inductor in particular, is a key component for impedance matching and for RF applications. It is designed such that it would exhibit a high Q-factor or simply Q (Quality-factor) for the specific inductance value and frequency range of operation [2]. Q-factor, on the other hand, is used as basis to compare and rate the performance of the inductor. Design tradeoffs between inductor

parameters are inevitable, so it is crucial that inductors be designed carefully for the specific requirements of the intended application.

2. Design Methodology

For the design and optimization of the inductor (or a spiral inductor), the following design rules and guidelines could be very useful:

- In order to reduce the resistive losses in the microstrip and to maximize the coupling between adjacent microstrip lines, a large ratio of the line width (W) to line spacing (S) is necessary. Narrow line spacing tends to increase the magnetic coupling between windings and this in turn causes an increase in the Q-factor and inductance for a given layout area [3]. Typical values of line spacing (S) for optimization range from 1-2 μm . Fig. 1 shows the simplified layout of the microstrip spiral inductor.
- Increasing the conductor/strip/metal width (W) would make the Q-factor more sensitive to changes in operating frequency. Optimum values of metal width range between 10-15 μm for most inductor designs

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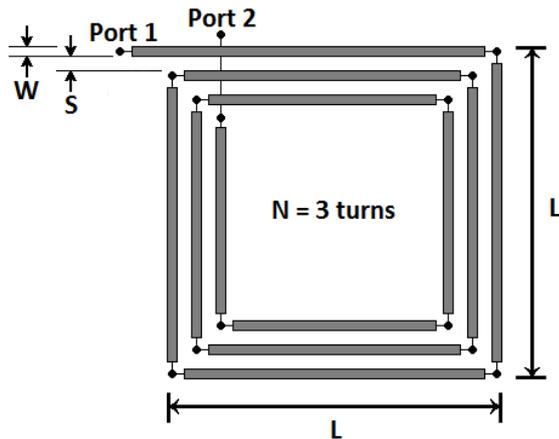


Fig. 1 Simplified layout of microstrip spiral inductor.

fabricated commercially [3].

- As the number of turns (N) of the spiral inductor increases, the outer dimension of the spiral (L) shrinks as well as the spacing between opposite sides of the spiral. This causes a drop in inductance and thus dropping the Q -factor because of negative mutual coupling.

- Q -factor of the spiral inductor is most sensitive to the thickness and resistivity of the metal layer used in fabrication [3]. An increase in the conductor thickness causes the inductance to increase. Q -factor could therefore be optimized by increasing the conductor thickness. But as frequency increases, energy is dissipated by the finite resistivity of the metallization as well as in the conductive substrate. Q -factor then decreases due to the increasing dissipation of energy at higher frequencies. Typical metal thickness ranges from 1-3 μm .

- The oxide layer isolates the metal conductors from the silicon substrate. A thicker oxide layer reduces the shunt parasitics and dissipation, which improves the inductor self-resonant frequency. Ideally, this results to a better Q -factor.

- Maintaining sufficient space between the inductor and its surroundings keeps unwanted parasitic effects from disturbing the inductor's electrical characteristics [3]. A spacing of at least five line widths ($5W$) is recommended.

For the design of the spiral inductor using freeware

tools, usually the first three guidelines are the only ones available for the designer or researcher to vary or characterize. Tools like the ASITIC (analysis and simulation of spiral inductors and transformers for ICs) [4, 5] and SpiralCalc (integrated spiral inductor calculator) [6-8], could be used to apply these design rules for the design and optimization of a spiral inductor. Both software tools are available for research and non-commercial purposes. In ASITIC, a technology file or tekfile is essential for the tool to run. Tekfile contains process specific parameters such as metal layer thicknesses and the sheet resistance of the various metal layers [3].

ASITIC and SpiralCalc were eventually used to design and optimize a spiral inductor. A sample value of 5.3 nH is set for the inductor design and for comparison using the two tools. In ASITIC, a tekfile `worstepi.tek` is necessary.

2.1 Spiral Inductor Design Using SpiralCalc

SpiralCalc uses simple and accurate expressions to calculate the DC (direct current) inductance of square, hexagonal, and octagonal spiral inductors given the input geometric parameters. To acquire the needed inductance of 5.3 nH, trial and error could be used with the turn spacing (S) and turn width (W) at optimal values which are 1 μm and 10 μm , respectively, as shown in Fig. 2.

| Stanford Microwave Integrated Circuits Laboratory | | | |
|--|------------------|-----------------------------|-------------------|
| Integrated Spiral Inductor Calculator | | | |
| Input Geometric Parameters | | | |
| No. turns, $n =$ | 4 | Turn spacing, $s =$ | 1 μm |
| Turn width, $w =$ | 10 μm | Outer diameter, $d_{out} =$ | 250 μm |
| <input type="button" value="Calculate"/> <input type="button" value="Defaults"/> | | | |
| Results | | | |
| | Square | Hexagonal | Octagonal |
| Modified Wheeler | 6.198 nH | 5.407 nH | 5.39 nH |
| Current Sheet | 6.19 nH | 5.4 nH | 5.362 nH |
| Monomial Fit | 6.18 nH | 5.57 nH | 5.505 nH |
| Reference: S.S. Mohan, M. Hershenson, S.P. Boyd and T.H. Lee, "Simple Accurate Expressions for Planar Spiral Inductances," <i>IEEE Journal of Solid-State Circuits</i> , Oct. 1999, pp. 1419-24. | | | |
| -Stanford University- | | | |

Fig. 2 SpiralCalc interface.

The modified Wheeler expression gives very good accuracy. This expression is obtained by modifying an expression that Wheeler obtained for discrete inductors [6, 8]. The current sheet expression is intuitive and is derived from electromagnetic principles by approximating the sides of the spiral by current sheets with uniform current distribution [7]. Lastly, the monomial fit expression is derived by data-fitting techniques. It is very well suited for optimization of circuits using geometric programming although it lacks intuitive derivation of the other two approximations [6, 7].

The input geometric parameters values in the SpiralCalc as shown in Fig. 2 that resulted to the desired inductance value could be used also to design the spiral inductor using the next tool which is ASITIC.

2.2 Spiral Inductor Design Using ASITIC

This tool is more complex and challenging to use than the SpiralCalc. It uses commands to create or design the inductor and analyze its characteristics and behavior as the frequency varies.

Commands like “square” and “spiral” are used to create a square spiral and a polygon spiral, respectively. “Spiral” command is often used because of its capability to create n-sided polygon spiral. It’s pretty straight forward to design using these commands. Input geometric parameter values must be provided and then it would create the layout of the spiral inductor. The values taken from the design of the inductor using SpiralCalc could be used as basis or for comparison for the design using ASITIC.

A better command to create an optimized spiral inductor is “optsq” for square spiral or “optpoly” for polygon spiral inductor. In this paper, “optpoly” command is used to create a polygon spiral inductor and optimize its Q-factor. An eight-sided polygon spiral inductor or an octagonal spiral inductor is designed using the ASITIC tools to compare it to results of the octagonal spiral inductor using

SpiralCalc. For the required inductance of 5.3 nH at a specific frequency, “optpoly” is the best command to use for it computes for the optimized input geometric parameters including the parasitics as shown in Fig. 3. A command “ind” or “inductance” could also be used to measure the inductance of the spiral inductor at a given frequency.

After the simulation using the “optpoly” command and if it simulates successfully, a layout is produced as shown in Fig. 4. The layout could be moved in the cell view by using the command “move” or “moveto”.

To compute for the inductance, Q-factor, resonant frequency, S-parameters and Y-parameters of the spiral inductor over a frequency range, “2portx” command is

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ASITIC
ASITIC version Grackle (Dywin)
Analysis & Simulation of Inductors and Transformers for ICs
Technology File Name? worstepi.tek

Reading .asitic init file...
ASITIC> optpoly

Desired Inductance, Accuracy (+/-)? (nH) 5.5 2
Name? fredd_inductor
Length (2*Radius)? 250
How many sides? 8
Spacing? 1
Min/Step/Max Width? 10 0,1 12
Metal layer? 5
Frequency? (GHz) 5

Simulation started at: Fri Jul 25 15:34:37 TST 2008
Simulation ended at: Fri Jul 25 15:34:40 TST 2008

Pi Model at f=5 GHz: Q = 956.2 m, 522.2 m, 7.36
L = 5.404 nH R = 10.95
Cs1 = 172.8 fF Rs1 = 2.739
Cs2 = 178.9 fF Rs2 = 2.98      Est. Resonance = 5.199 GHz
Found: n =5.0000, w =10.0000, s =1.0000, L =5.4038 (nH), Q = 0.9562
ASITIC>

```

Fig. 3 ASITIC interface, with command “optpoly”.



Fig. 4 ASITIC spiral inductor layout.

used. Each parameter could be modified by using the command “set”. Setting the mode of the analysis into “fast” would hasten the simulations. Setting it “slow” uses the EM (electromagnetic) analysis and it would take more time to run and finish the simulations. In this paper, “fast” mode is used.

3. Results and Analysis

The results from simulations in ASITIC are saved into an output file. The output file could be modified by using the command “set”, setting the output file into the desired output filename. For the SpiralCalc tool, the results are already shown in Fig. 2 given the input geometric parameters. Table 1 shows the comparison of the data and results of the two tools at DC.

The data and results for the two tools are somehow comparable to each other. But this only applies at zero frequency or at DC. Table 2 tabulates the S-parameters of the spiral inductor from frequency 0-10 GHz. These parameters are essential for the analysis of the behavior and characteristics of the spiral inductor.

The resonant frequency of the spiral inductor is where the Q-factor first reached zero (except for DC). It could be obtained by examining the results of the simulation in the ASITIC. Table 2 shows the data for the inductance and Q-factor of the spiral inductor. ASITIC uses more complex formula to obtain the inductance and Q-factor versus frequency of the spiral inductor. For this paper, the following formulae shown in Eqs. (1) and (2) are used to obtain and approximate the inductance (L) and the Q-factor of the spiral inductor.

$$L = \frac{\text{imag}(Z_{11})}{2\pi f} \quad (1)$$

$$Q = \frac{\text{imag}(Z_{11})}{\text{real}(Z_{11})} \quad (2)$$

From the data in Table 2, the resonant frequency

happened to be close at 5.179 GHz. At this point, the Q-factor is almost zero and can be observed that L and Q-factor shifted to negative values above this resonant frequency. This is because the spiral inductor tends to act as a capacitor above the resonant frequency. To have a better view of the behavior of the inductor, Figs. 5 and 6 show the plots of L and Q-factor versus the frequency, respectively.

Table 1 Results comparison of the two tools at DC.

| Parameters | SpiralCalc | ASITIC |
|---------------------|------------|----------|
| No. of turns (N) | 4 | 5 |
| Metal width (W) | 10 μm | 10 μm |
| Line spacing (S) | 1 μm | 1 μm |
| Length/diameter (L) | 250 μm | 250 μm |
| No. of sides | 8 | 8 |
| Inductance | 5.39 nH | 5.354 nH |

Table 2 Inductance and Q-factor.

| Freq (MHz) | Z ₁₁ (real) | Z ₁₁ (imag) | L (nH) | Q-Factor |
|------------|------------------------|------------------------|---------|----------|
| 1 | 11.277 | 0.034 | 5.411 | 0.003 |
| 50 | 11.279 | 1.676 | 5.335 | 0.149 |
| 100 | 11.286 | 3.353 | 5.336 | 0.297 |
| 500 | 11.492 | 16.899 | 5.379 | 1.471 |
| 1,000 | 12.146 | 34.682 | 5.52 | 2.855 |
| 2,000 | 15.371 | 77.554 | 6.172 | 5.045 |
| 3,000 | 24.675 | 145.635 | 7.726 | 5.902 |
| 4,000 | 64.546 | 305.091 | 12.139 | 4.727 |
| 5,000 | 1,138.118 | 1,088.212 | 34.639 | 0.956 |
| 5,179 | 2,290.873 | -4.74 | -0.146 | -0.002 |
| 5,500 | 532.346 | -1,017.228 | -29.436 | -1.911 |
| 6,000 | 94.166 | -495.627 | -13.147 | -5.263 |
| 7,000 | 18.879 | -228.976 | -5.206 | -12.129 |
| 8,000 | 8.707 | -141.034 | -2.806 | -16.198 |
| 9,000 | 6.149 | -92.782 | -1.641 | -15.089 |
| 10,000 | 5.814 | -57.861 | -0.921 | -9.952 |

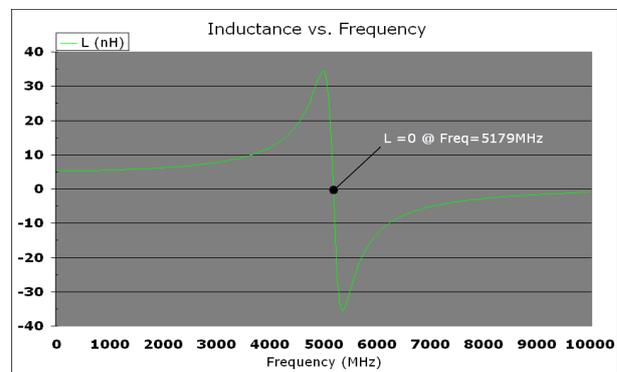


Fig. 5 Inductance plot versus frequency.

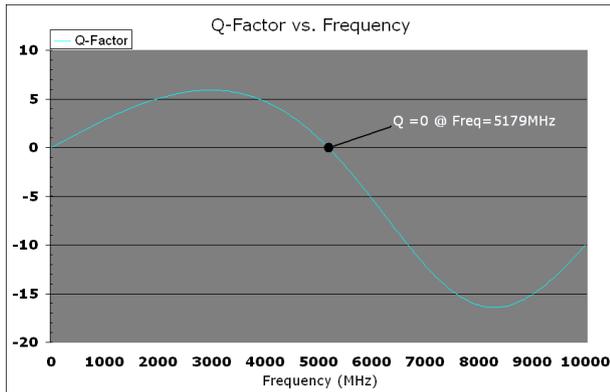


Fig. 6 Q-factor plot versus frequency.

4. Conclusion

Spiral inductor designs using ASITIC and SpiralCalc were studied and compared along with the hand-calculations using the formulae in Eqs. (1) and (2). A discrepancy in inductance values was observed between the two tools. ASITIC included the parasitics in computing for the actual values of the inductance while Eqs. (1) and (2) were applicable only for ideal inductor. In addition, SpiralCalc used three different approximations for computing inductances but were valid only at DC and for limited design purposes. ASITIC revealed greater accuracy and could also be used for 3D electromagnetic analysis as well as 2D planar simplifications.

Complex tradeoffs among technology specifications and design parameters exist and should be carefully handled when designing an inductor, to optimize the quality and its performance. It is worth noting that inductors do not always behave as inductors as they may shift to capacitor operation at frequencies above resonance. Thus, it is crucial that inductors be designed for their effective frequency range of

operation, satisfying the requirements of the end-product application.

Acknowledgments

The author would like to express great appreciation to Prof. Maria Theresa De Leon, Ph.D. of Microelectronics and Microprocessors Laboratory at University of the Philippines for the technical support and to the STMicroelectronics Calamba NPI Team and Management Team.

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