DESIGN AND ANALYSIS OF SYMMETRICAL SPIRAL INDUCTORS FOR RFIC

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In this paper are discussed symmetrical inductors. They have significant advantages over classical 2-port inductors in silicon-based RFIC, e.g. higher Q factor, higher self-resonant frequency, and smaller inductor size. 2-port classic and 3-port symmetrical inductors with different electrical parameters and sizes are simulated and compared.

Keywords: Symmetrical spiral inductors, RF, analysis, design

1. INTRODUCTION

Inductors are basic component in radio-frequency integrated circuits (RFICs). They are primarily used in circuits, such as voltage-controlled oscillators (VCOs), filters, low-noise amplifiers (LNAs) or power amplifiers (the final stage of integrated transmitters and transceivers). In these circuits, it is often desirable and necessary to fabricate inductors on the same substrate as the rest of the RF circuit in order to reduce the size of the overall device and increase its reliability.

On the other hand, monolithic or spiral inductors frequently occupy majority of the chip area and there is significant cross coupling to the adjacent components. Important parameters of monolithic inductors, including the quality factor (Q), self-resonant frequency, and the area needed to be optimized or comprised in the RF design. In the last few years there are many efforts to improve on-chip inductor performance. One of the resent directions is to merge two symmetric inductors into a differential (symmetric and center-tap) inductor. One can treat such inductor as to single-end inductors inter-wound symmetrically to become a three-port inductor. A center-tap port is usually tied to a dc voltage source as an ac ground and is shared by the two coupled inductors. Thus, the two inductors share the same flux area. Significant advantages of such structures mentioned in the literature are the reduced by half inductor central empty area and the enhancement of quality factor due to reduction in the substrate loss.

The paper discusses symmetrical inductor structures designed using four metal layer 0.35μm SiGe BiCMOS technology, where the top metal layer thickness is much larger than the rest of the metal layers. A common design guideline that is utilized is creating all inductor windings on the top metal layer, because of the larger thickness. This arrangement would minimize the series resistance and increase the Q-factor. A library of ten symmetrical inductors with different inductance values (in the range from 1.5nH to 6nH) is created. The difference is not only in their nominal value, but also in their design and electrical parameters. Six classical square single-layered spiral inductors are selected form the existing library solely in order to make the comparison. All inductors, classical and symmetrical are fabricated using the fourth thick metal layer of the AMS 0.35µm SiGe BiCMOS technology. Third metal layer is used for the transition and the connection of the inner port of the spirals.

2. ANALYSIS OF SYMMETRICAL SPIRAL INDUCTORS

The analysis of spiral inductors is made with Spectre Direct Circuit Simulator using industrial standard CAD design software Cadence. S-parameter analysis is employed. The symmetrical inductor model from fig. 1 is utilized. It represents the whole structure including metallization, oxide and substrate parameters and is described by a coupled inductor and coupling capacitor components similar to those of a common two-port inductor. The coupled inductors are presented by self inductances, series resistances and coupling coefficients.

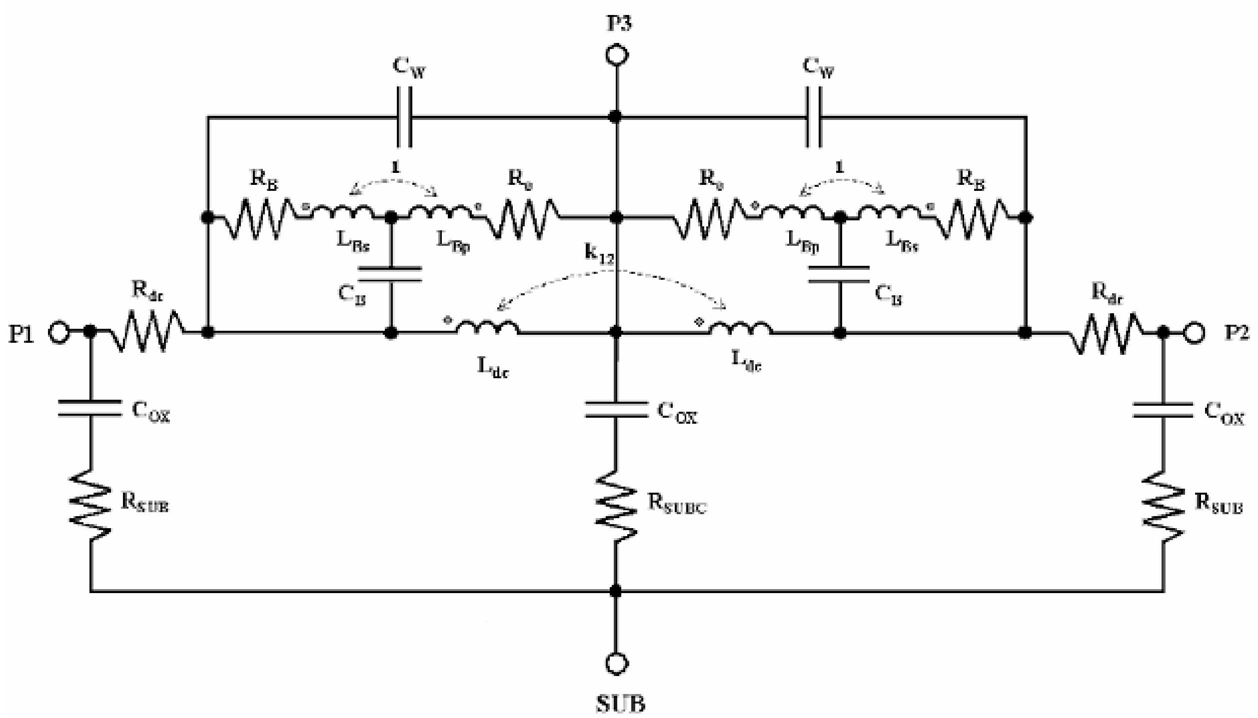

Fig. 1. Symmetrical inductor model

S-parameter analysis linearizes the circuit around the DC operating point and computes S-parameters of the circuit with two-port statements. At least one port (sinusoidal input source with 50Ω characteristic impedance) should be used in the circuit. Spectre simulator performs a linear small-signal analysis and converts the response of the circuit at each port into S-parameters. Then the extracted S-parameters are transformed into Y and Z-parameters in order to calculate the values of interest.

Finally, the main inductor parameters are calculated using the following equations:

Effective series inductance (L)
$$L = \frac{\mathrm{Im}(Z)}{\omega} \tag{1}$$

Effective series resistance (R) $$R = \mathrm{Re}(Z) \tag{2}$$

Quality factor (Q) $$Q = \left|\frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)}\right|, \tag{3}$$

where $\omega = 2\pi f$.

The impedance Z for classical inductors is $Z=1/y_{11}$ and for symmetrical - Z=z11r+z22r-z12r-z21r+j(z11i+z22i-z12i-z21i).

Test circuits utilized for the investigation of symmetrical and classic spiral inductors are shown at fig. 1 and fig. 2, respectively. The center node of the symmetrical spiral can be connected to ground potential, left open or connected to a voltage source with different potential.

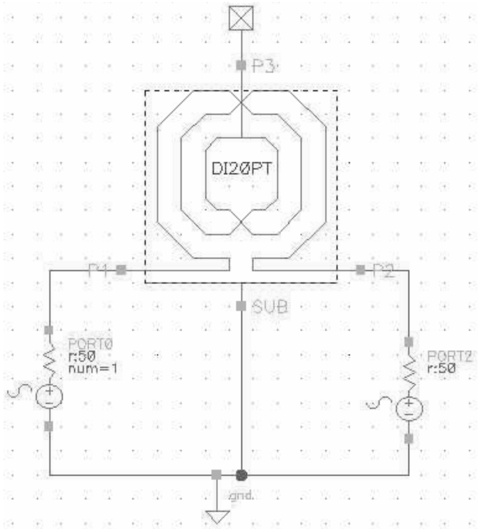

Fig. 2. Analysis Circuit for Symmetrical Inductor

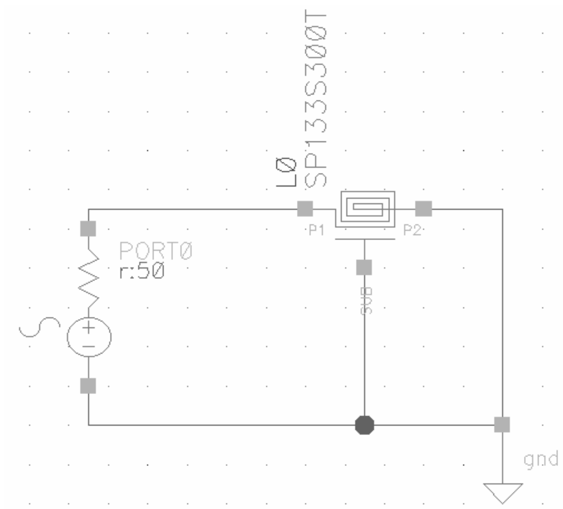

Fig. 3. Analysis Circuit for Classic Inductor

In table 1 is summarized the data for the nominal inductance L and series resistance R, maximum quality factor (Qmax) and the frequency at which it appears, and self-resonance frequency (SRF) of symmetrical inductors with different sizes, while in table 2 is presented the same information for different classical spiral inductors.

Table 1. Symmetrical Spiral Inductors

Symmetrical inductor	Size, µm	L, nH	Qmax	R, Ω	SRF, GHz
DI1	186x186	1.5	14,5@13GHz	14.59	21,42
DI2	216x216	2	14@10GHz	9.339	13.59
DI3	252x252	2.5	14@8GHz	12.74	12.76
DI4	294x294	3	14@6GHz	11.78	10.47
DI5	342x342	3.5	14@5,3GHz	11.51	9.16
DI6	236x236	4	10@4,8GHz	16.14	8.33
DI7	286x286	4.5	10@3,8GHz	15.95	7.2
DI8	324x324	5	11@3,5GHz	15.28	6.66
DI9	345x345	5.5	11@3,2GHz	15.08	6.12
DI10	392x392	6	10@3GHz	13.74	5.85

Table 2. Classical Spiral Inductors

Classic inductor	Size, μm	L, nH	Qmax	R, Ω	SRF, GHz
SP1	250x250	1.5	10.87 @ 3.50GHz	3.069	18.09
SP2	250x250	2	9.87 @ 4.40GHz	5.952	17.83
SP3	250x250	2.4	9.16 @ 2.45GHz	3.874	12.47
SP4	250x250	3.1	8.91 @ 3.02GHz	5.567	10.15
SP5	300x300	4.9	9.07 @ 2.406GHz	8.792	7.727
SP6	300x300	6	7.36 @ 2.92GHz	17.269	7.82

Typically, integrated inductors are used in the gigahertz range. Thus, the inductors are studied from 1GHz up to 20GHz. So the behavior of each inductor at wide range of working frequencies can be observed. The analysis data is collected and compared for typical mean conditions. In fig. 4 and fig. 5, respectively, is given the graphical representation of the quality factor and inductance as a function of frequency for different symmetrical inductors.

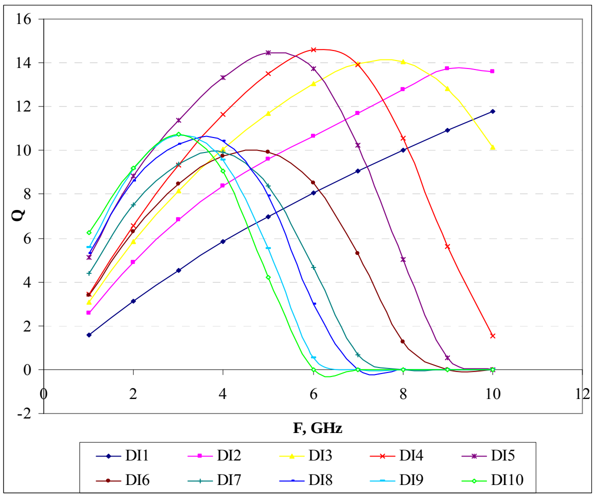

Fig. 4. Quality factor of symmetrical inductors with different inductance value versus frequency

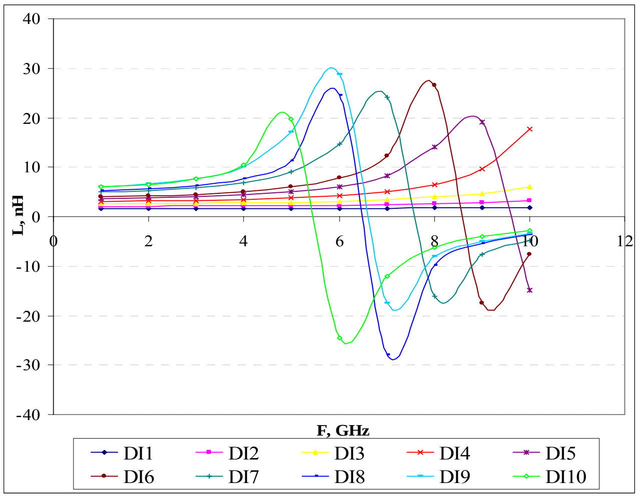

Fig. 5. Inductance value of symmetrical inductors versus frequency

Additionally, worst case analysis is made for symmetrical inductors in order to see the deviation of the basic inductor parameters from the nominal value (typical mean condition - TM). For integrated inductors the two worst case conditions are entitled high Q (LQ) and low Q (LQ). High Q represents the most favourable combination of process parameters and working conditions. It is expected that the behavior of the on-chip inductor will enclose between these two boundaries.

In fig. 6 is compared and depicted the quality factor versus frequency of one symmetrical inductor (DI4) for different working conditions (TM, HQ, and LQ). The variation of Q in different cases is significant and must be taken into consideration when these inductors are used.

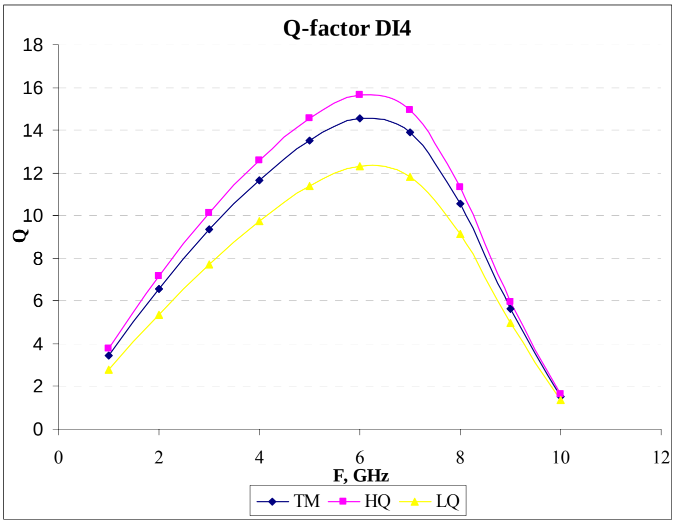

Fig. 6. Q-factor versus frequency of DI4 for different working conditions (TM, HQ, and LQ)

A comparison of classical inductors and symmetrical inductors with different inductance values is made. In fig. 7 to 12 are presented the results for the quality factor and inductance of spiral inductors with nominal value 1.5nH, 3nH and 6nH.

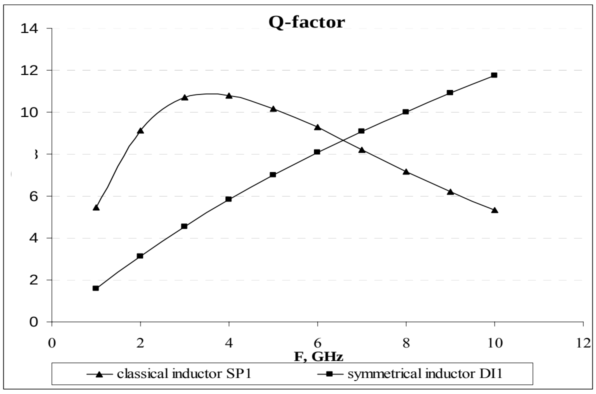

Fig. 7. Q-factor versus frequency for 1.5nH classical and symmetrical inductor

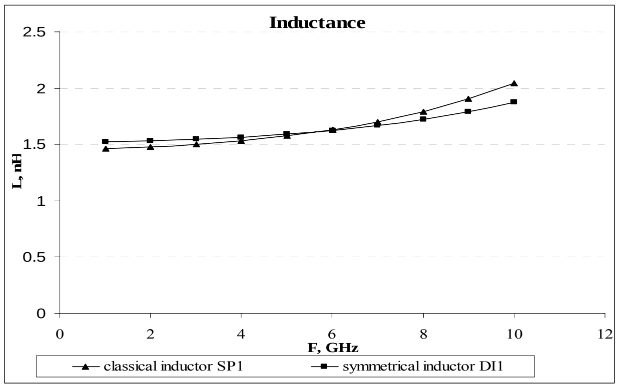

Fig. 8. Inductance versus frequency for 1.5nH classical and symmetrical inductor

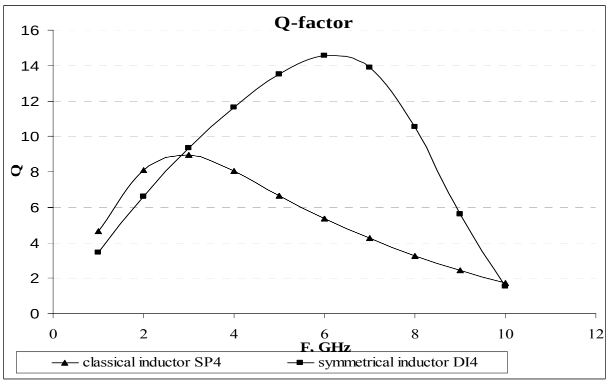

Fig. 9. Q-factor versus frequency for 3nH classical and symmetrical inductor

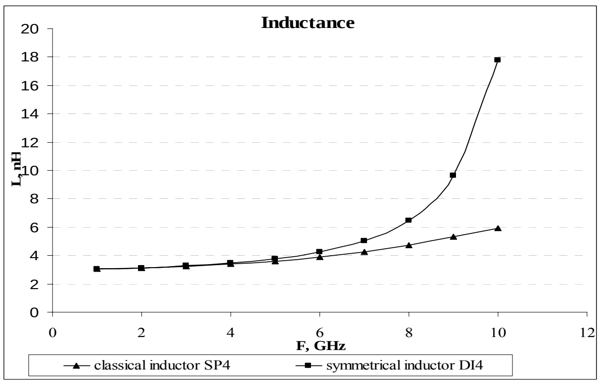

Fig. 10. Inductance versus frequency for 3nH classical and symmetrical inductor

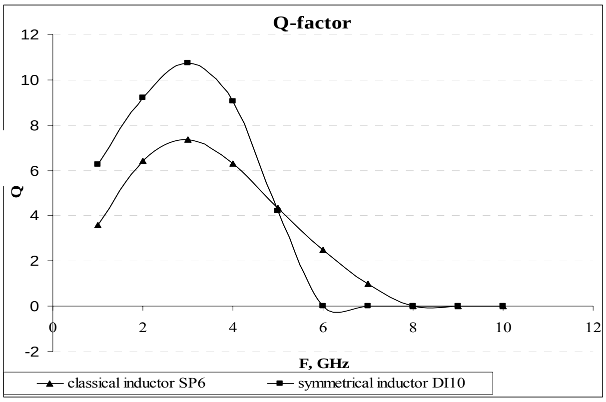

Fig. 11. Q-factor versus frequency for 6nH classical and symmetrical inductor

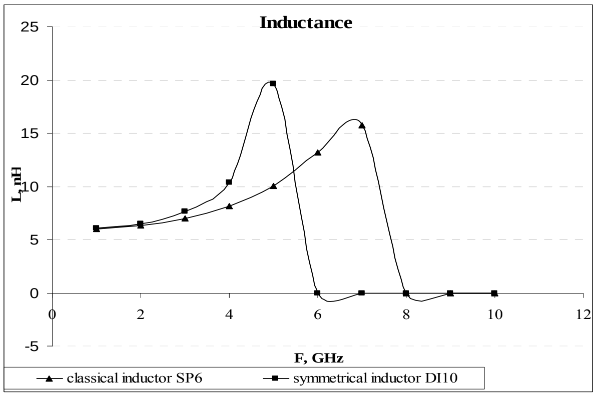

Fig. 12. Inductance versus frequency for 6nH classical and symmetrical inductor

It is evident that classical square spiral inductors have lower quality factor and self-resonance frequency and the maximum of quality factor appears at lower frequencies compared with the symmetrical inductors. The advantages of symmetrical inductors are compelling. This dependency is kept with the increase of inductance. From the comparison of 3nH inductors can be seen that the Q factor of symmetrical inductor is almost two times higher then the classical one, but at higher frequency. The frequencies of Qmax for 6nH inductors are almost equal. However the Q-factor of symmetrical inductor is significantly higher.

3. Conclusions

Symmetrical spiral inductors have significant advantages over the classical square spiral inductors. They can achieve better quality factor, work at higher frequencies, and have higher inductance value in comparison with the same area classical inductor. The symmetrical inductor model is more complicated, but it is still easy to implement it in Spectre circuit simulator or other Spice like simulator.

4. Acknowledgement

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5. References

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