On-Chip Interconnect Compatible Physical Modeling of RF Spiral Inductor

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Abstract

▪Spiral Inductor-On-Silicon (SIOS) are an integral part of modern RF CMOS chips. A majority work on RF inductor design and parameters extraction are based on field-solvers which are known to be very accurate but having disadvantage of heavy computational overhead.

▪Present work proposes a physics based model based on basic electromagnetic theory which gives an analytical procedure for obtaining rectangular spiral inductors commonly used in RF inductors.

▪The approach is on the line of inductance modelling for interconnects due to which the proposed model can be integrated with the layout tool of VLSI interconnect.

▪The results have been verified with the tool FASTHENRY - a field simulator. The model has been verified for rectangular and square geometry having grounded guard-ring occupying same area.

Introduction

▪Micro inductors have become an integral part of RF CMOS ICs, because of its application in analogue circuits such as low noise amplifier, band-pass filters, voltage controlled oscillators, mixers, etc., due to low power consumption, low fabrication cost and adaptability to integration. For design of RF ICs in addition to RF modelling of CMOS devices, it is necessary to have a compact model of inductors for use in circuit simulation such as SPICE.

▪Inductor modelling by enlarge is empirical where analytical expression have been available. Field simulators are commonly used for inductor's characterisation and modelling but it has very high computational overhead and makes it impractical to use it within a circuit simulator. A need of a compact physical model of inductors has been there for a long time and several attempt have been made to develop inductor model that can be used for a circuit design along with active components.

▪The present work attempts to develop on inductors model of a commonly used square and rectangular structure based on basic laws of electromagnetic.

▪It may be mentioned here that unlike many microwave applications in CMOS VLSI RF circuits the ground plane which provide the return path to the signal current through the inductor is coplanar.

▪Most of the analytical modelling of inductor assumes ground plane at the bottom of the substrate and not much theoretical work on coplanar ground is reported.

▪Experimental work with coplanar ground are not much supported by any theoretical work. The present investigation makes use of concept of partial inductance in the computation of inductance of the branches forming the spiral inductors.

▪Here we are introducing a coplanar square spiral structure of inductor with ground guard-ring for reference and which is depicted in figure 1

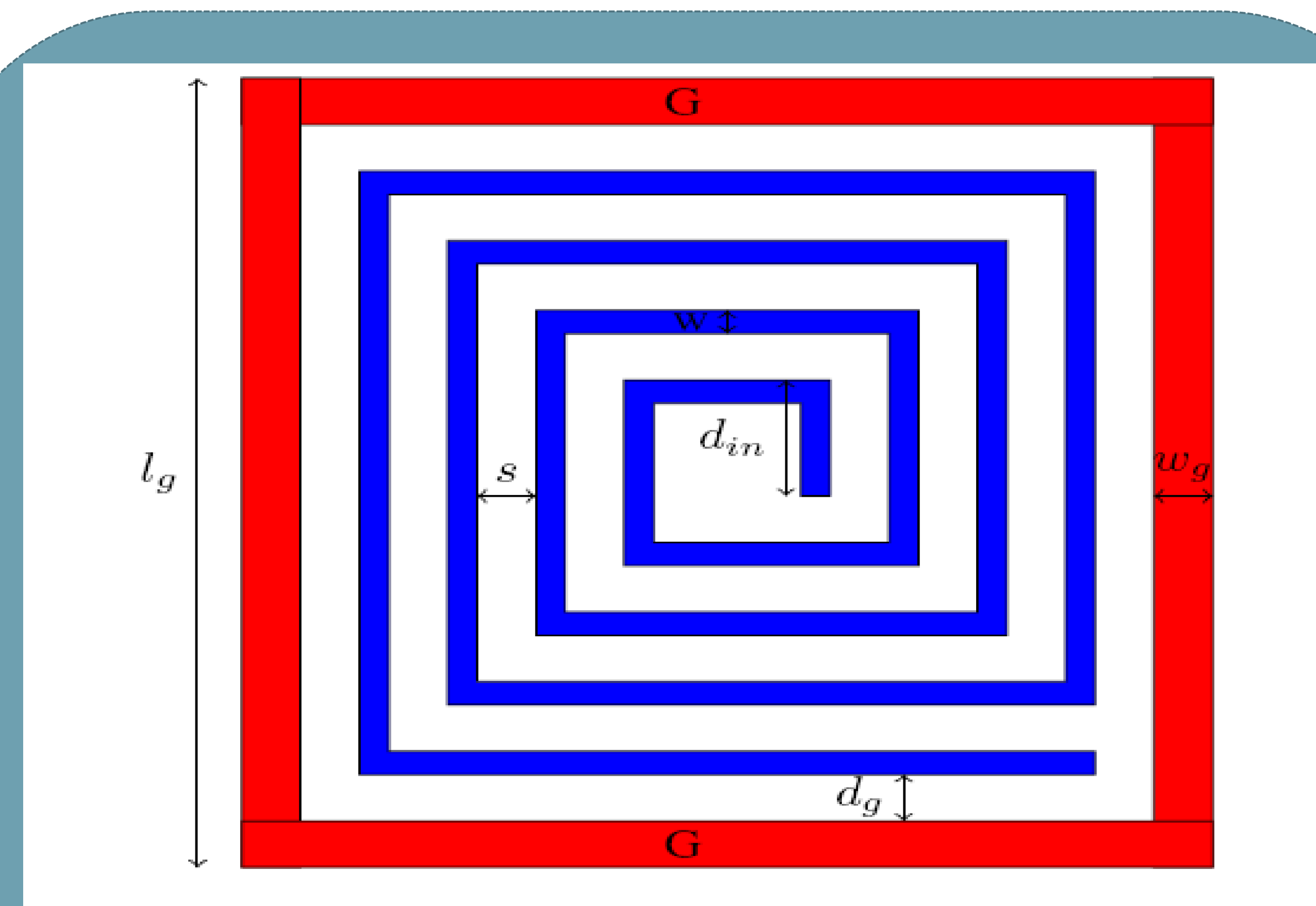

Fig. 1. Basic structure of square spiral inductor with grounded guard-ring for reference

- Notations Used:
  - G – Ground guard-ring
  - d_{in} – Inner most segment length
  - w – Width of spiral inductor
  - s – Spacing between turns of spiral
  - d_g Spacing between ground wire and outer segment of spiral
  - w_g – Width of ground wire
  - l_g – Length of ground wire
  - L_i – Total self inductance of any segment i
  - L_{ij} – Total mutual inductance between segment i and j

Modelling

we make following simplified assumptions in modelling:-

➢The rectangular strips of the spiral is approximated by cylindrical wires for applying well established formulae available in electromagnetic.

➢For a conductor sandwich between two ground planes irrespective of its position between the ground planes, the current is assumed to be equally divided in two ground return path.

➢The width of the ground conductor plane has been restricted to the 3 times of width of signal conductor.

➢The present work is restricted to the evaluation of low value inductance and does not take into account the high frequency phenomenon such as skin effect, proximity effect and substrate losses due to eddy current.

▪Here it is necessary to mention that the all signal wires are of different length and have two ground wires of same length but at different distance d_{g1} and d_{g2} for return path of current which form a parallel loop for inductance calculation, taking the current divided equally in both ground wire.

▪To derive a compact model, the inductor decomposes into even and odd segments that is each turn decomposes into 4 branches as depicted in Fig. 2.

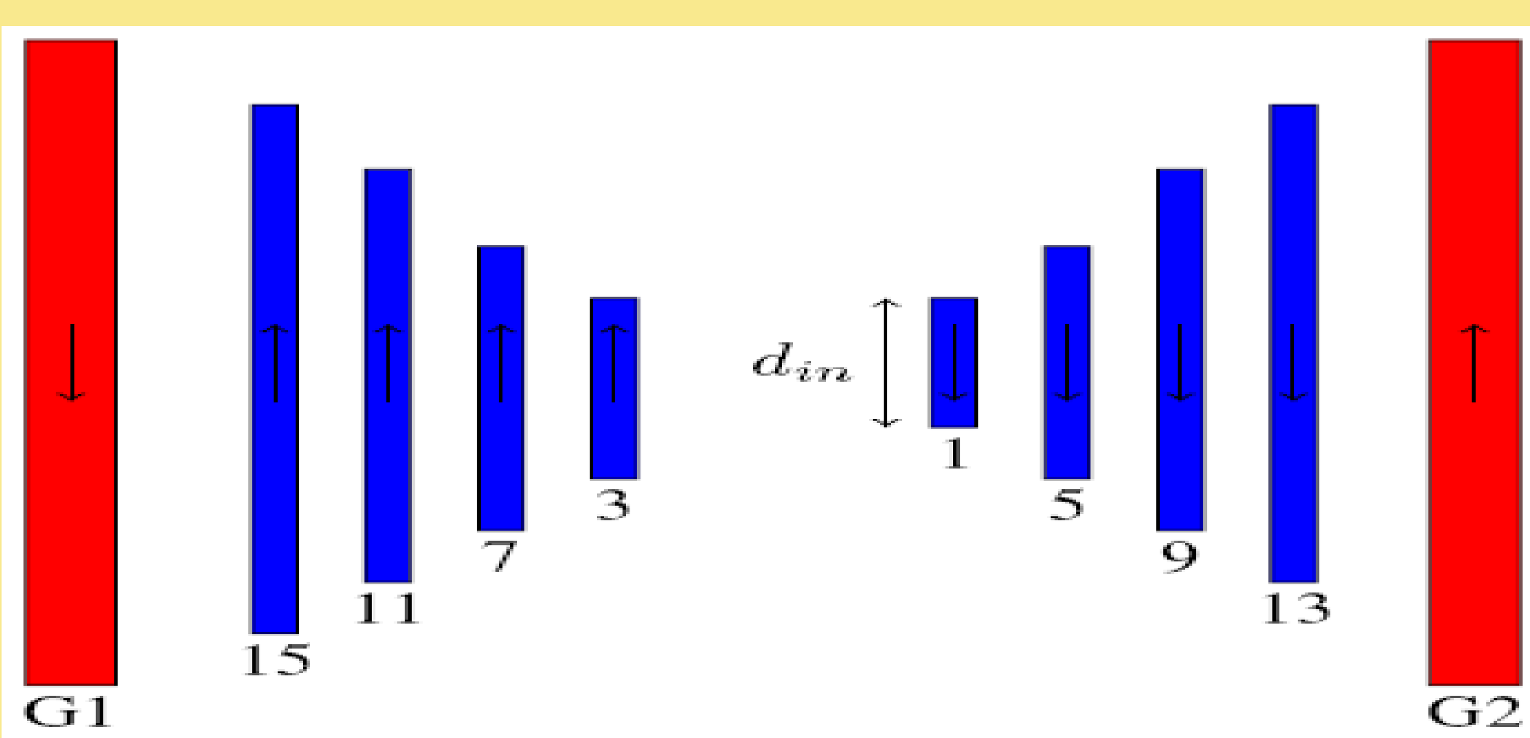

Fig. 2. Odd/Vertical Segments of Spiral

▪Equations derived from basic electromagnetic laws considering above assumptions:-

$$L_{in} = (1 + 0.5)\frac{\mu_0}{8\pi}$$

$$L_{ex1} = \frac{\mu_0}{2\pi}\log\frac{(r+d_{g1})^{3/2}(w+d_{g2}+r)^{1/2}}{r^{3/2}(d_{g1}+w+d_{g2}+r)^{1/2}}$$

$$L_{ex2} = \frac{\mu_0}{2\pi}\log\frac{(r+d_{g2})^{3/2}(w+d_{g1}+r)^{1/2}}{r^{3/2}(d_{g2}+w+d_{g1}+r)^{1/2}}$$

$$L_i = l_{wi}(L_{in} + L_{ex1} + L_{ex2})$$

Where r is the radius of signal wire, L_{in} is internal inductance of segment and L_{ex} is the external inductance of partial loop with respective ground wire.

▪Coupling inductance between two wires is the quantity of flux linkage enclosed by any signal wire due to the magnetic flux induced from other signal wire in an overlap area.

▪ Coupling can be of positive or negative type depending on the direction of current by which we can determine the respective direction of magnetic flux by *corkscrew rule or right hand grip rule.*

Acknowledgment

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Controlled Experiment

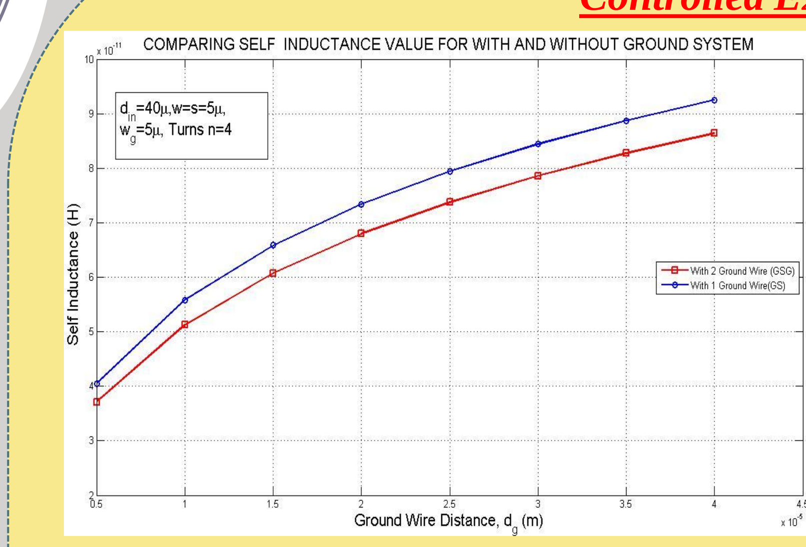

Fig. 3. Comparison Plot of Inductance value for a signal wire with one (GS) and two ground (GSG) system

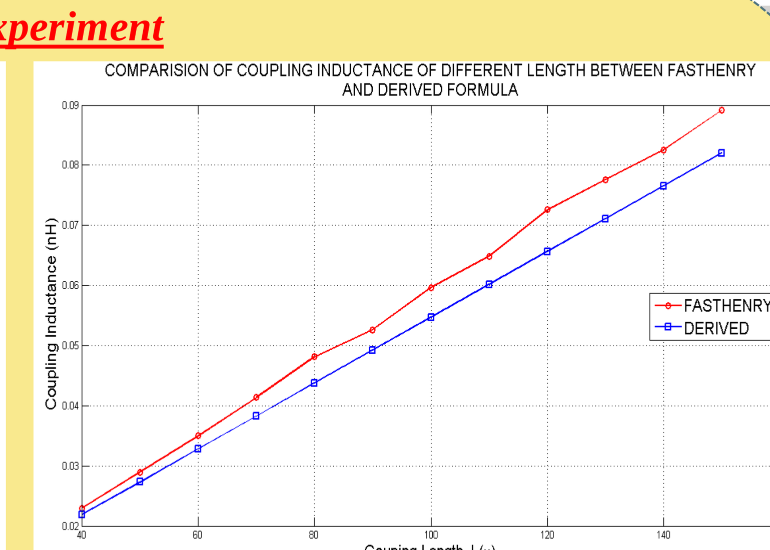

Fig. 4. Coupling Inductance plot for different length of segments of GSG structure

•In fig. 3, it is observe that GSG configuration leads to lower value of inductance due to cancellation of flux linkage from second ground. Secondly in both cases as distance of ground with respect to signal is increased, the inductance value increases.

• fig. 4 investigate the variation of coupling inductance with overlapping length between two signal wire of different length in GSSG structure and observe that the variation of mutual inductance is almost linear with the coupling length from both proposed model and FASTHENRY.

• In fig.5., the variation in mutual inductance is studied for GSSG structure by changing the distance between the signal wires keeping d_g same. It is noticed that as the distance between signal wires increases, mutual inductance decreases.

• But mutual inductance increases if we increase the d_g keeping the distance between signal wire same.

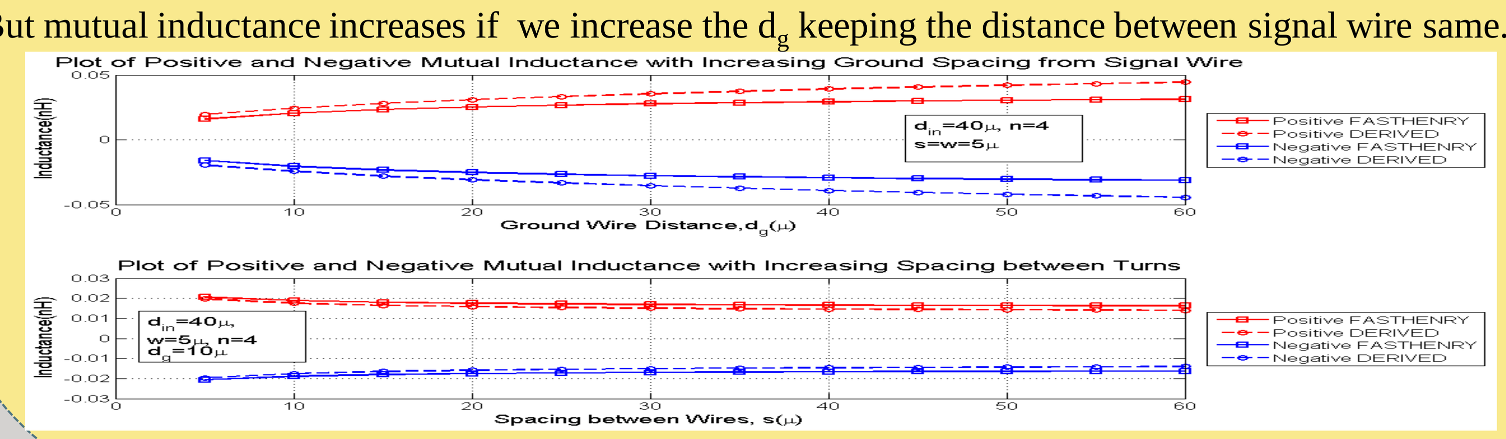

Fig.5. Positive and negative mutual inductance plot tiling d_g and S as variable

Result

• In chip design, the optimization of silicon estate is consider to be significant factor which is defined as the inductance per unit area in the spiral designing.

•Therefore, the optimal design of inductor per unit area has been undertaking for square and rectangular geometry for same area as invariant with equal width and spacing.

Turn	FastHenry	Derived	Error(%)
1	0.0738	0.07067	4.24
2	0.3177	0.302	4.54
3	0.5899	0.56513	4.3
4	1.091	1.01886	7.1

Table 1: Square spiral within reference square guard ring area

Turn	FastHenry	Derived	Error(%)
1	0.09506	0.09072	4.56
2	0.3824	0.36557	4.4
3	0.6557	0.6282	4.2
4	1.225	1.167	4.71

Table 2: Rectangular spiral within rectangular guard ring having same area of reference square spiral

Turn	FastHenry	Derived	Error(%)
1	0.1087	0.1031	5.2
2	0.3957	0.3733	5.67
3	0.6927	0.6484	6.4
4	1.309	1.2315	5.92

Table 3: Rectangular spiral within reference square guard ring area

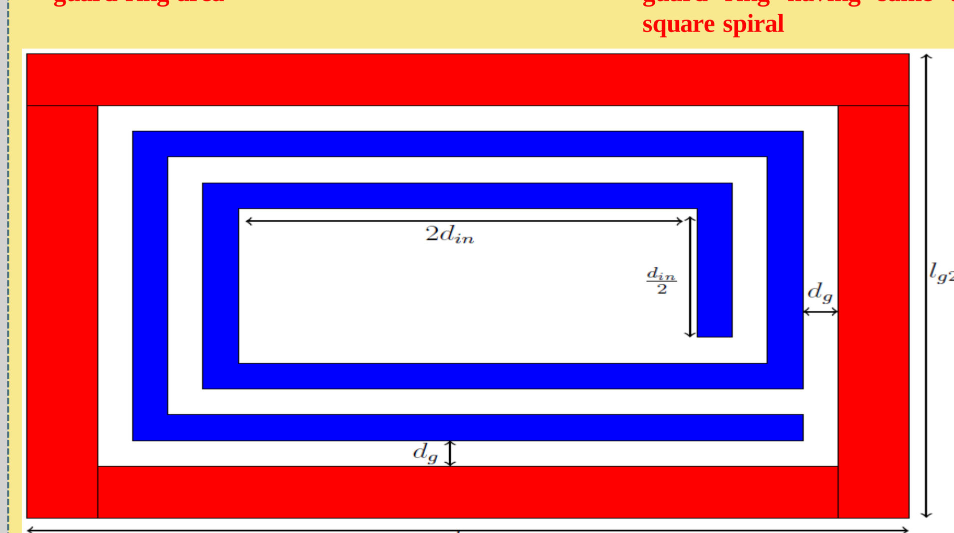

Fig. 6 : Rectangular spiral within rectangular guard ring having same area of reference square spiral

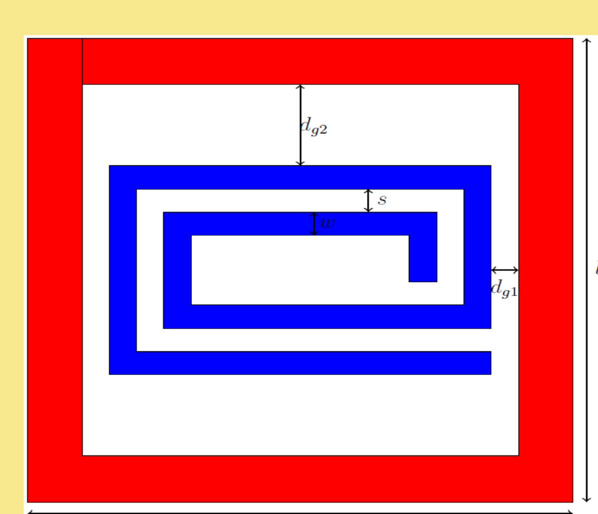

Fig. 7: Rectangular spiral within reference square guard ring area

• Table 1 gives the result of inductor value computation for different number of turns of a square spiral for dimensions d_{in} = 40μ, s=w= w_g = 5μ and d_g = 10μ as computed by proposed model and predicted by FASTHENRY. It is found that the value computed by model is within 5% of error.

• Table 2 relates to fig. 6 where the area of rectangle bounded by the guard ring is same as the square spiral with ground guard ring. This structure leads to increase in inductance by 30% compared to the square spiral structure.

•Similarly Table 3 relates to the Fig.7, where the area remains same as of previous but structure of ground guarding is of square and structure of spiral inductor within it is of rectangular one.

•From the study of Table 3 it is seen that the third configuration with rectangular spiral within square reference guard-ring leads to 47% more inductance with reference square spiral which is the highest among the three structures. It is also can be seen that the error between the valve by proposed model and by FASTHENRY remains in the range of 5% to 7% for three structures.