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Design and Simulation of On-Chip Spiral Inductor and Spiral Spacing Effects

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Abstract: Recently, with the rapid growth of the demands in wireless communication products such as mobile phones and wireless network, low cost and high performance onchip radio-frequency devices are strongly needed. One important limitation in achieving higher levels of integration and further reduction of fabrication costs in the front-end of microwave transceivers is set by the difficulty of achieving high-Q on-chip inductors with smaller size. In the research work spiral inductors are simulated while achieving appreciable inductance and terminal voltage.

Keywords: On chip, silicon, FEM, inductor, spirals, terminal voltage.

I. INTRODUCTION

In the development of integrated circuits, passive devices have traditionally played a minor role in comparison with active devices. The most obvious reason is the area requirement. Active devices are continuously down-scaling while passive devices remain large. At low frequency designers emulated passive functionality with active components to make their products more area and cost-effective. When low loss, high-quality devices were needed, they were usually connected externally on-board rather than on-chip. This is possible as long as few external components are needed and the package parasitics are negligible in comparison with characteristics of the external device at the operating frequency. Inductors and transformers play a decisive role in the performance of circuits operating at high frequencies. Emulated active inductors employing several transistors are difficult to realize at higher frequency as the gain of active devices drops and the stability and linearity problems become severe. In addition, actively emulated inductors have a finite dynamic range, require voltage supply range to operate and inject additional noise into the circuits. In contrast with digital circuits which use mainly active devices, on-chip passive components are necessary and imperative adjuncts to most RF electronics [1-2]. These components, which include inductors, capacitors, varactors, and resistors, have been known as performance as well as cost limiting elements of radio frequency (RF) integrated circuits. While all of these components can be realized using MOS technology, their specific designs necessitate special consideration due to the requirement of high quality factor Q at relatively high frequencies. Inductors in particular are critical components in oscillators and other tuned circuits. For low-frequency applications, passive devices can be connected externally, but as the frequency increases, the characteristics of the passive devices would be overwhelmed by parasitic effect [3]. For instance, a voltage-controlled oscillator (VCO) of 10 MHz needs a tank inductance on the order of several µH, whereas at 10 GHz the inductance is around 1 nH. It's impossible to access such a small inductance externally, since the inductance associated with the package pin and bond wire can exceed 1nH. As a result, on-chip passive components are commonly used in RF applications. A typical spiral inductor has geometry as shown in Fig. 1. Qualitatively, the spiral inductor consists of a number of series-connected metal segments. In each segment, time varying conductive current will flow due to a time-varying voltage impressed on the segment. In addition, due to self-inductive and mutual-inductive effects (i.e. magnetic flux linkage from segment to segment) a time varying emf is produced with a phase 90° leading the impressed conductive current. Furthermore, due to the presence of the substrate and closely spaced metal segments, charge on each segment will cause charge to accumulate and flow at the surface of the substrate as well on neighboring segments. This charge will flow as a current 90° lagging the impressed voltage. Due to the finite conductivity of the substrate, the induced substrate charge must flow through the lossy substrate, acting as an additional source of loss.

The losses in an inductor are of two types; conductor loss and substrate loss. The conductor loss in an inductor is proportional to its series resistance. The series resistance increases significantly at high frequencies due to skin effect and magnetically induced eddy currents. Eddy currents produce non uniform current flow in the inner portion of spiral inductors, with much higher current density on the inner side of the conductor than on the outer side. Eddy currents in the substrate are inaccurately modeled in the approaches available for the analysis of inductors. Hence, compact modeling expressions for skin effect, proximity effect, and eddy-current induced substrate losses are highly desirable.

Skin and proximity effects result from eddy currents. In an imperfect conductor, an increasing magnetic field will penetrate the material to some extent. It induces voltage and causes current to flow in such a way as to weaken the magnetic field and prevent the field from penetrating further into the conductor. If this magnetic field is generated by the

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conductor itself, then the phenomenon is called "skin effect" and if generated by an adjacent time-varying current carrying conductor, the phenomenon is called "proximity effect". Proximity effect is experienced by the conductor even if it does not carry current [4-7]. As frequency rises, the resistance of a metal segment will increase due to the skin effect. The skin depth of metal is given by,

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

where 'ρ' is the resistivity of the metal, 'μ' is the permeability and 'f' is the frequency of operation. Skin effect and the current loop formation are shown in Fig.2 (a-b).

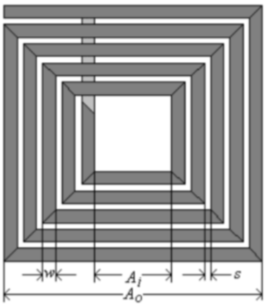

Fig. 1 Layout of a typical square spiral inductor.

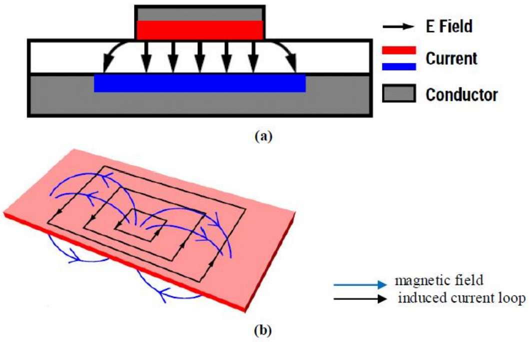

Fig. 2 (a) Current restriction due to skin effect (b) induced current loops causing skin effect.

The presence of a current carrying conductor in the vicinity of an inductor changes magnetic fields near the inductor and hence the current distribution inside it. Proximity effects reduce wire inductance because currents in different conductors re-distribute themselves to form a smaller current loop at high frequencies. A spiral inductor is affected by proximity effect due to conductors carrying currents in the same direction as well as from those carrying currents in the opposite directions as shown in Fig.3. M+ denotes the mutual inductance between conductors carrying current in same direction and M- denotes mutual inductance between conductors carrying current in opposite direction. The proximity effect due to conductors carrying current in opposite directions in a typical spiral inductor can be neglected if the centre is hollow. To minimize proximity effects due to opposite current carrying conductors, it is recommended to have smaller fill ratio. This may be possible at the cost of inductor area [8-10].

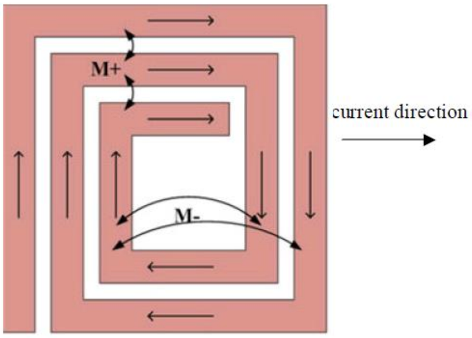

Fig.3 Current directions in a planar Spiral inductor.

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II. SIMULATION PROCESS

FEM based tool is a high performance full wave electromagnetic simulator that employs the finite element method (FEM), adaptive meshing, and brilliant graphics to give insight to 3D electromagnetic problems. Design creation using COMSOL involves the following

- Parametric model generation – The geometry of the model is created, the boundaries and excitations are then defined.
- Analysis setup – The solution setup and the frequency sweeps are then defined.
- Results – 2D reports and field plots are then obtained.
- Solve Loop – The solution process is fully automated.

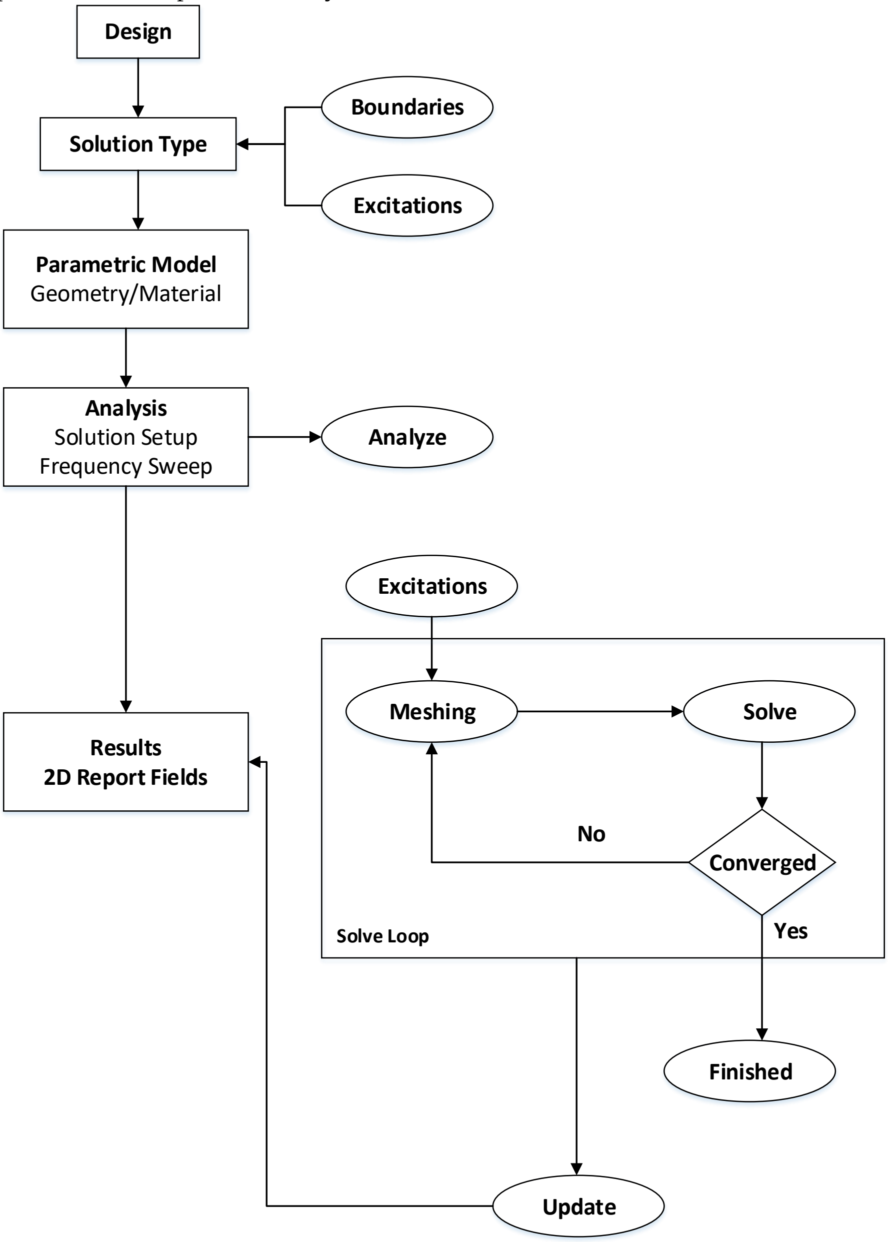

Fig. 5 Simulation process flow.

The integration of radio-frequency (RF) systems in silicon (Si) requires that the fabrication process provides high-quality passive components. The performances of RF systems are strongly influenced by the performance of inductors. Inductors are important elements that require high quality factor (Q-factor), high self resonance frequency, and small size for desired inductance. Many researchers have been studying inductors for Si RF integrated circuits. Most of them have used measurements to construct models. While this technique is most practical, it does not permit optimization. Otherwise,

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researchers have used commercial 3D electromagnetic simulators to design and analyze inductors. Device structure is shown in Fig. 6

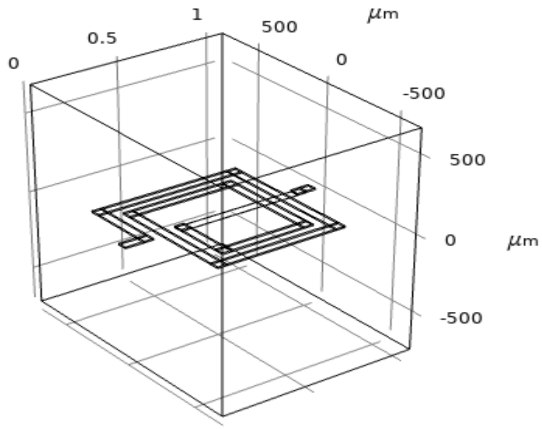

Fig. 6 Designed spiral inductor.

III. RESULTS AND DISCUSSIONS

A 4-ring spiral coil structure is modeled with varying level of ring thickness. The dimensional parameter used to create the geometry are

- Number of coils 4
- Width of coils 50um
- Gap spacing between the coils 50um
- Thickness of the rings d3= 10um, d2=8um, d1=6um, and d0=4um (decreasing order of thickness from outer ring)
- Thickness of the rings d3= 4um, d2=6um, d1=8um, and d0=10um (increasing order of thickness from outer ring)

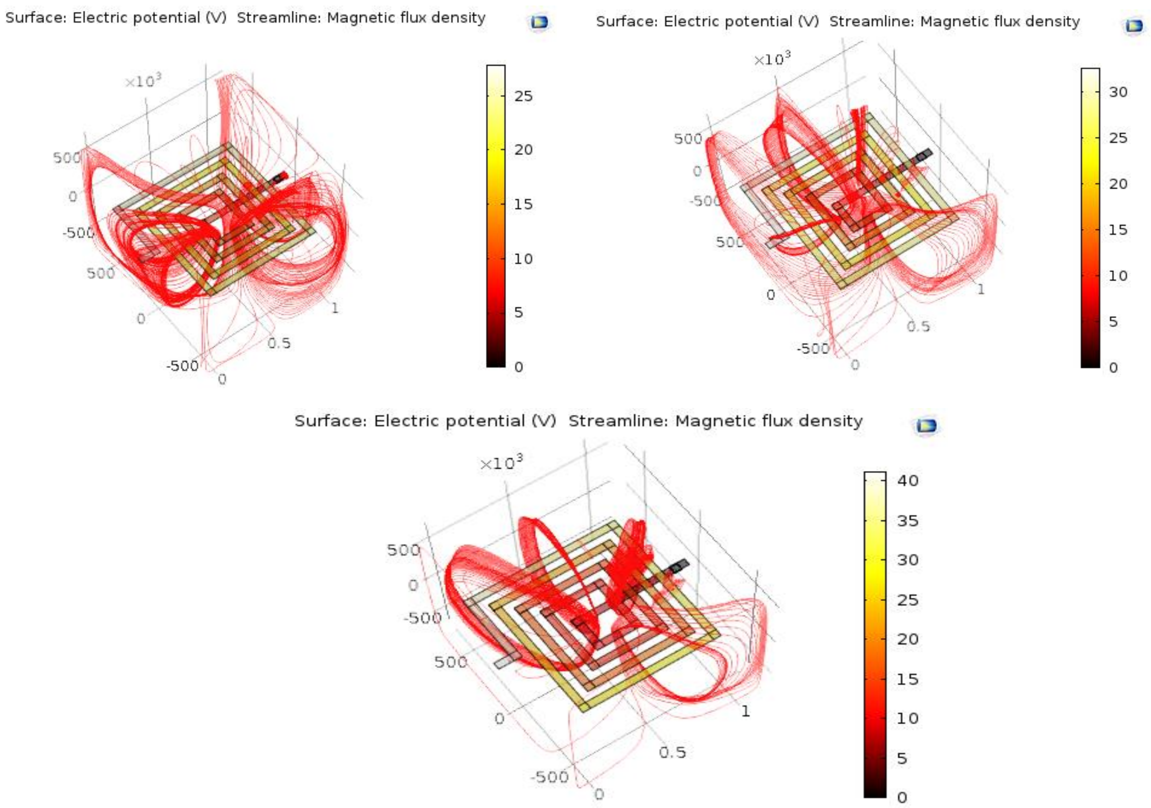

Fig. 7 Magnetic field response of designed spiral inductor.

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Inductance of the spiral inductor depends upon the thickness of the rings. Gradually increasing the thickness of rings starting from the outer ring will cause the decrease in the inductance. Gradually decreasing the thickness of rings starting from the outer ring, increases the inductance but is still lower than as compared inductance with constant thickness.

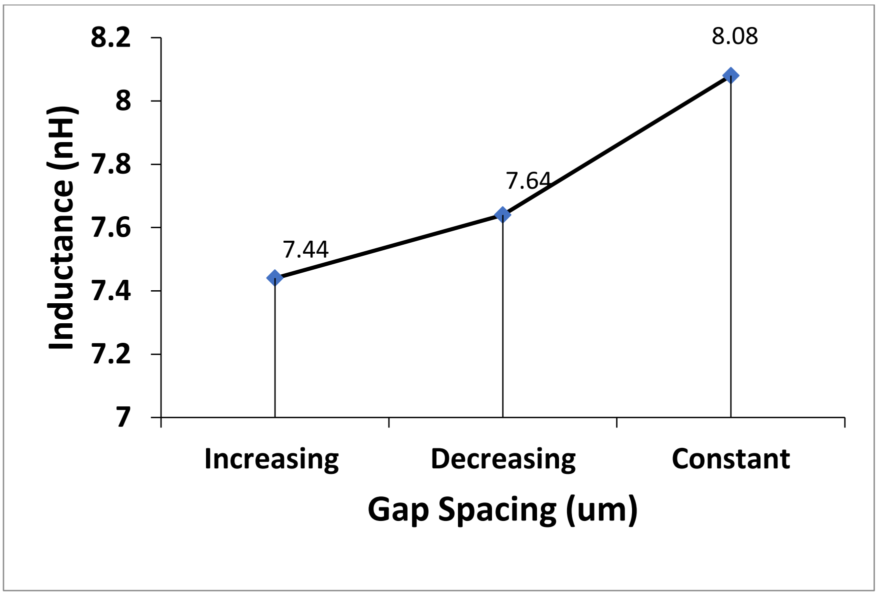

Fig. 8 Calculated values of inductance.

The geometry of spiral inductor is modelled to estimate the effect of increasing as well as decreasing order of gap spacing between the coils. In the first model gap spacing is increased from out ring with the step size of 10um. The gap of outer ring is kept at 10um, which is gradually increased and the inner ring gap is 40um. In the second model the outer ring gap is kept at 40um and inner ring gap is kept at 10um. All the rest of the dimensional parameters are kept same as that of 4 ring geometry.

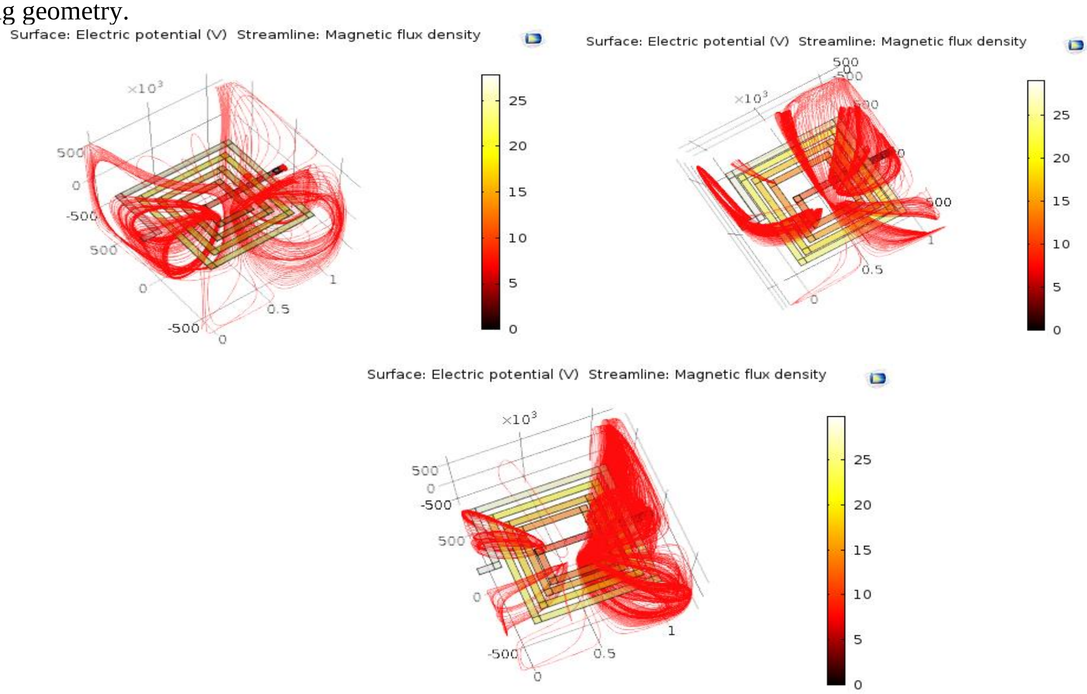

Fig. 9 Magnetic field response of designed spiral inductor.

Inductance of the spiral inductor increases if the gap spacing between rings is varied in such a way that outer ring in having minimum spacing and inner ring is having maximum spacing. If the reverse order of spacing is considered the inductance is still higher than the constant spacing spiral inductor.

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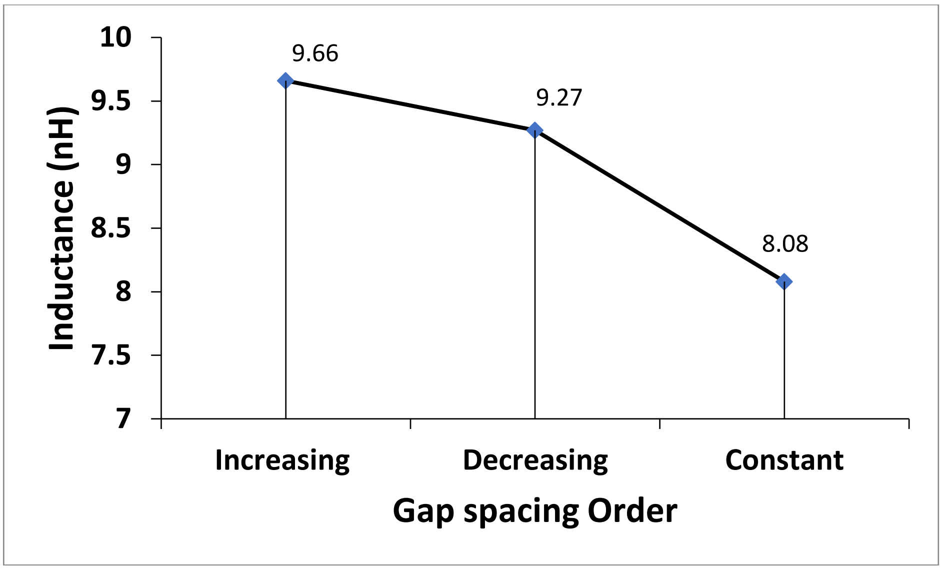

Fig. 10 Inductance of simulated spiral inductor.

Terminal Voltage obtained is higher for the spiral inductor which is having maximum gap spacing in the outer ring and minimum spacing in the inner ring of the spiral inductor.

IV. CONCLUSION

In this research work onchip spiral inductors are modeled and simulated. Various effect of geometry parameters was investigated and device performance were analyzed. Effect of variable gap spacing between the coils of spiral inductor: if the gap spacing in varied in such a way that out ring is having minimum gap spacing the inductance rises drastically. If the spacing order is reversed i.e. outer ring with maximum gap spacing the inductance value still be higher than constant gap spacing spiral inductor. Effect of thickness of coils on spiral inductor: Inductance is directly proportional to thickness of the coils in spiral inductor.

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