Power Efficient Wireless Inductive Coupling for RF Telemetry Applications

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***Abstract*— In this paper we introduce a novel inductive link for wireless transmission to enhance power transfer efficiency and power transfer density for RF telemetry applications. Here, we present the design of square spiral inductor on FR4 substrate for different number of turns. Various simulations based on the incipient models were done by varying geometric parameters. We vary the number of turns from 5 to 9 and find out their effect on Inductance (L), Quality factor (Q) and Self resonant frequency (SRF).The development of inductors for RF telemetry applications is studied. For, this square spiral inductors were also fabricated on FR4 substrate by designing the Layout of the inductor using Tanner L-edit tool. Simultaneous change of different parameters with number of turns is presented that allow circuit designer to optimize the integrated inductor in RF telemetry with minimum cost, risk and time. HFSS simulation results are shown to verify the theoretical results. An inductive link can be formed between a pair of fabricated square spiral inductors and subsequent simulation results can be used for calculation of power transfer efficiency and power transfer density.**

***Keywords*— Coupling, spiral inductor optimization, power transfer efficiency, inductive link, telemetry.**

I. INTRODUCTION

An inductive link two magnetically coupled coils that constitute a transformer is so far the only viable solution to wirelessly energize high performance implantable microelectronic devices with high power requirements [1]. Radio Frequency Telemetry System combines Radio Frequency (RF) technology with novel micro-inductor antennas and signal processing circuits for RF telemetry of real time, measured data, from MEMS sensors, through electromagnetic coupling with a remote powering/receiving device [2]. In radio frequency integrated circuits (RFICs), spiral inductor represents one of the major components of the RF ICs that dominates circuit performance and most frequently used passive devices in modern RFICs. A successful design and simulation of RFICs depends on accurate modelling and characterization of spiral inductors.

Wireless communication systems are on rapid growth and has stimulated research in low-cost, low-power, and high-performance CMOS RF integrated-circuit (IC) components for system-on-chip solutions [3]. The inductor is a basic component and very vital in designing radio frequency matching networks, load circuits of voltage controlled oscillators, filters, mixers and many other RF circuits [4]. In this paper the performance analysis of square spiral inductor using HFSS v11.0 tool is presented. Geometry parameters of the inductor structure and process technology parameters are varied in order to determine how they affect the inductor performance such as inductance, Q-factor and SRF [5]. Self resonant frequency and S-parameters were calculated for various numbers of turns. The effect of number of turns of inductor on Q and inductance were simulated as well as calculated and it was found that inductor with more number of turns gives best quality factor and inductance. The values of Q and Inductance are highly suitable for on chip Bio-MEMS inductor used in RF telemetry application [2]. The parameters of equivalent lumped model of inductor are mathematically calculated and found close to the simulated results. Finally, square spiral inductors were also fabricated on FR4 substrate by designing the Layout of the inductor using Tanner L-edit tool.

II. CONCEPT OF INDUCTIVE POWER LINK

Fig. 1 shows the concept of an inductive power link and its equivalent circuit [6]. The RF input signal with a power amplifier in the transmitter is modelled as a voltage source in the primary resonator. The receiver is modelled as a resister R_L in the secondary resonator. k is the transformer coupling coefficient, and L_1 and L_2 are self-inductance in transmitter and receiver coils, respectively. R_1 and R_2 model the losses in the coils. C_1 and C_2 are capacitors including parasitic and external capacitance to create a resonance at the transmitter and receiver side. Standard inductive coupling uses a frequency well below the self-resonant frequency of the inductors, therefore parasitic capacitance (C_1, C_2) are typically ignored in this case. Resonant inductive coupling, however, uses this capacitance to resonate with the inductors, increasing the flux linked between transmitter and receiver. While high power transfer efficiency is critical for low power systems, area-constrained systems can require larger power transfer through smaller area coils at an acceptable loss in efficiency. With a fixed distance between two coils, larger coils result in larger k and higher efficiency.

However, using larger coils requires more area, and it ultimately decreases the power transfer density.

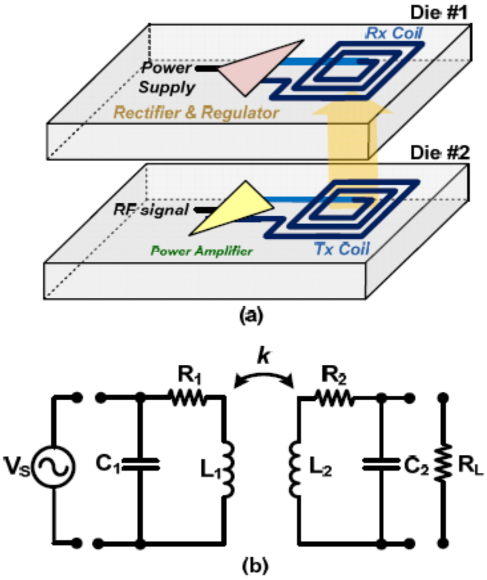

Fig. 1 (a) Concept of wireless inductive power link (b) Equivalent Circuit

III. DESIGN OF INDUCTOR

Fig. 2 shows the model that is most often used to characterize a square spiral inductor [8]. Inductors were designed using commercially available high frequency structure simulator tool for different number of turns from 5 to 9 by taking into considerations that 0.5 mm thick copper metal spiral was placed on 1.6 mm thick FR4 substrate. On the other hand, a simulation-based approach provides more flexibility to the designer to select an inductor of desired performance and to make the design cost effective [7].

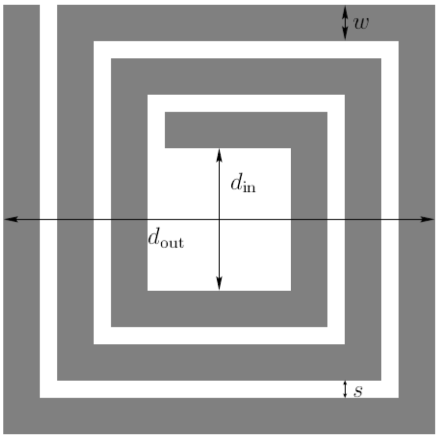

Fig. 2 Dimensions of square spiral Inductor

Here, we vary the number of turns from 5 to 9, the outer diameter (d_{out}) of the inductors, from 44mm, 52mm, 60mm, 68mm, to 76mm with the dimensions width (w) = 2mm, spacing (s) = 2mm, and inner diameter (d_{in}) = 8mm for every inductor.

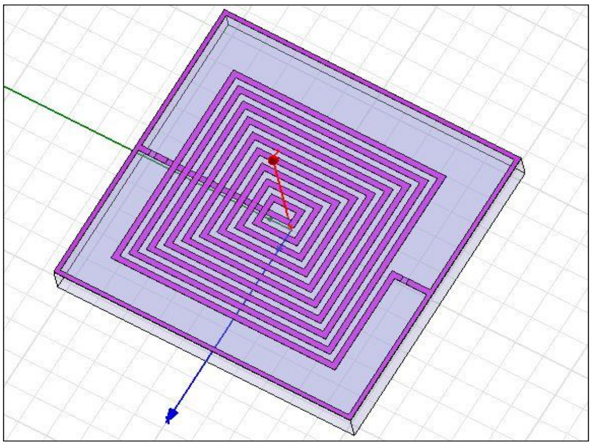

Fig. 3 Inductor design with n = 9 and d_{out} = 76mm

For the performance analysis and characterization of inductors, the simulator calculates the S-parameter and then converts to Y-parameter [9], from which Inductance and Quality factor are extracted by equation (1) and (2) respectively.

L = -img (1/Y_{11})/2*pi*f ------------ (1)

Q = img (Y_{11})/real(Y_{11}) ------------ (2)

Where Y_{11} is the input admittance and *f* is the operating frequency. Self-resonance of a circuit occurs at a frequency when its reactance equals to zero value. Therefore at SRF inductance and Q are zero. SRF and peak Q are extracted from the Q plot.

A. *S-parameters and Self-Resonant Frequency*

The S-parameters refer to the way in which travelling currents and voltages in a transmission line are affected when they meet discontinuity caused by the insertion of a network into the transmission line. This is equivalent to the wave meeting electrical impedance differing from the lines of characteristic impedance. At resonant frequency the inductor acts purely resistive and above this frequency will begin to act like a capacitor.The S-parameters and Self Resonant Frequency of inductors having 5 turns to 9 turns was calculated and S_{12} of 5 turn inductor was come out to be -41.49 at 92 MHz, similarly the S_{12} of 6, 7, 8, and 9 turn inductor was -41.58 at 68 MHz,-43.09 at 51 MHz, -46.20 at 43 MHz, and -44.39 at 34 MHz respectively.

B. *Effect of number of turns*

A set of spiral inductors were designed with various geometric dimensions and technology parameters and simulated using HFSS tool. Number of turns of inductor is an important geometrical layout parameter to consider since it determines the overall size and performance of the inductor. By increasing the number of turns from 5 to 9, inductance is improved by 0.7 µH to 5 µH, quality varies from 15 to 19 and SRF falls down from 92 MHz to 34 MHz. In order to find out the effect of number of turns on inductance (L), Quality factor (Q) and SRF (Self Resonant frequency), we have plotted a number a graphs as shown here:

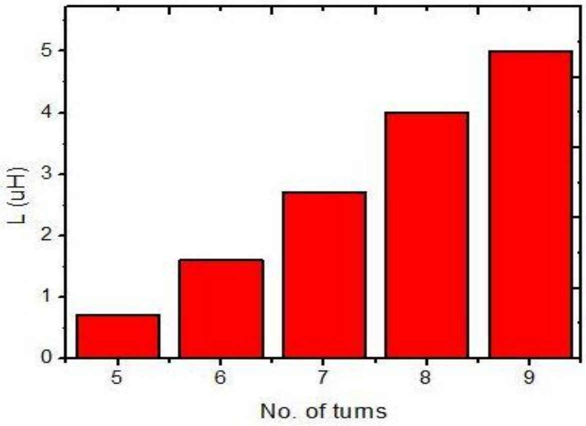

Fig. 4 Change in Inductance (L) with respect to no. of turns

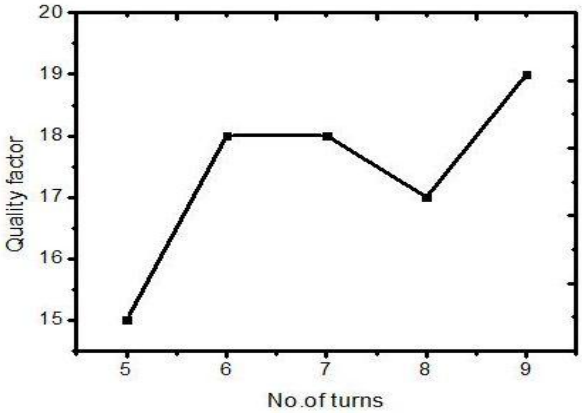

Fig. 5 Change in Q with respect to no. of turns

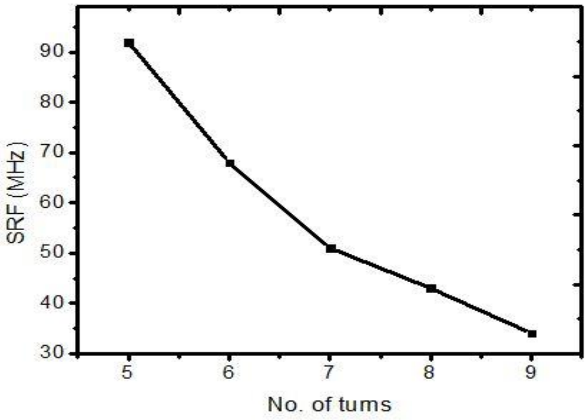

Fig. 6 Change in Self resonant frequency with respect to no. of turns

IV. FABRICATION OF SQUARE SPIRAL INDUCTOR

The square spiral inductors are fabricated on FR4 substrate by designing the Layout of the inductor using Tanner L-edit tool and then fabricating the inductors following various fabrication steps. While it is primarily a VLSI design tool, it is also flexible enough to do micromachining design and printed circuit board layout. Inductors were designed for different number of turns from 5 to 9 by taking into considerations that 0.5 mm thick copper metal spiral was placed on 1.6 mm thick FR4 substrate.

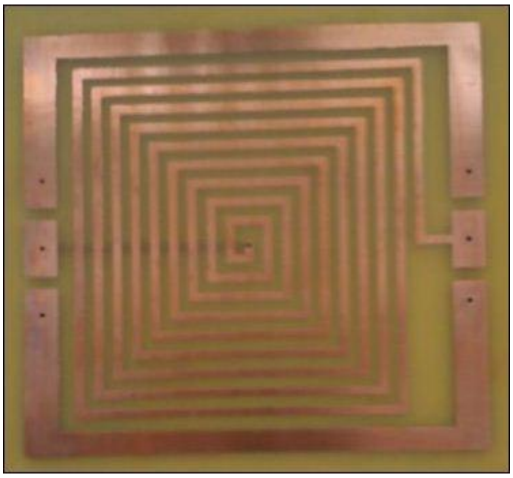

Fig. 7 Fabricated 9-turn Square spiral inductor

V. MATHEMATICAL CALCULATION AND RESULTS

The Lumped-element equivalent model of spiral inductor [9] for parameter extraction is shown in Fig. 8.

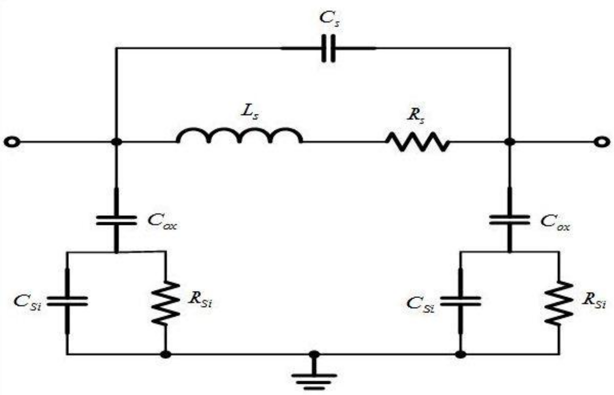

Fig. 8 Lumped-element equivalent circuit of spiral inductor

The mathematical expression for inductance and quality factor can be given as follows [9]:
Bryan’s equation [10] for the inductance calculation
$L = (0.0241)\ an^{5/3} \ln [8(a/c)]$
And
Q-Factor calculation

$$Q = \frac{\omega L}{R_s} \cdot \left[\frac{R_p}{R_p + \left[\left(\frac{\omega L}{R_s} \right)^2 + 1 \right] R_s} \right] \cdot \left[1 - \frac{{R_s}^2 (C_s + C_p)}{L} - \omega^2 L (C_s + C_p) \right]$$

Fringing capacitance calculation (C_s) = 28.04fF.
Parasitic capacitance calculation (C_p) = 13.29fF.
Accumulated Sheet resistance (R_s) = 4.095 Ω/sq.
Resistance of the conductive substrate (R_p) = 4.58 KΩ/cm.

Parameters of the lumped element equivalent model assuming FR4 as a material of fabrication were calculated for 9 turn inductor. Inductance is 5 µH and Q_{max} is 19.Both inductance and Q_{max} was calculated as well as simulated and results matched each other.

The inductive power link entire equivalent circuit and its secondary equivalent circuit [6] are shown in Fig. 9.

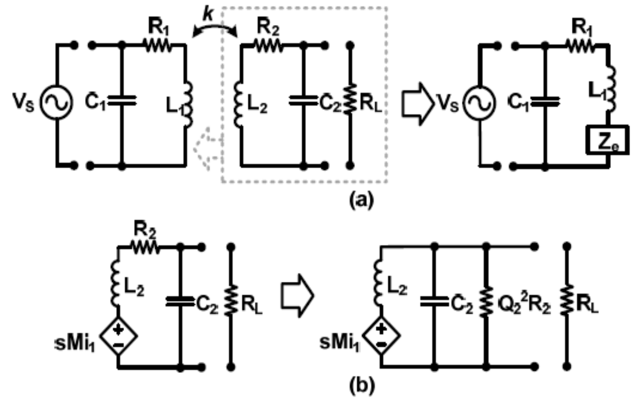

Fig. 9 (a) Entire equivalent circuit (b) Secondary equivalent circuit

The total power efficiency of the inductive power link is calculated as: $\eta = 0.47$ i.e. 47%.
And, The power transfer density is calculated as:
$P_{Den} = 23.12\ mW/mm^2$.

VI. CONCLUSION

The performance of a wireless inductive link can be improved by using resonant inductive coupling. For low power systems and high power efficiency, higher k and Q are required. However, in order to increase the absolute power transfer amount, power density is critical, and the optimal value of k to maximize power density depends on the distance and coil technology. Systematic characterization of square spiral inductor on FR4 substrate using HFSS v11.0 simulation tool is discussed. Performance of square spiral inductors are analysed with the variation in layout geometry parameters and different process technology parameters. By increasing the number of turns from 5 to 9, inductance is improved by 0.7 µH to 5 µH, quality varies from 15 to 19 and SRF falls down from 92 MHz to 34 MHz and found that the inductor with 9 turn provides highest inductance(L),Quality factor (Q) at low SRF. Equivalent circuit of spiral inductor is studied and it is found that both simulated and calculated results match each other. Layout is designed using Tanner L-edit tool and square spiral inductors are fabricated on Fr4 substrate. An inductive link can be formed between a pair of fabricated square spiral inductors and subsequent simulation results can be used for calculation of power transfer efficiency of 47% and power transfer density of 23.12 mW/mm^2. The software designed, simulated, and fabricated inductors need to be put through subsequent testing for verifications and in Future the electronic Interface with the proposed Inductor can be used in various RF telemetry applications ([11]-[12]).

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