Stacked Spirals for Biosensor Telemetry

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Abstract—This paper presents an inductive power transmission coil for biosensor-based telemetric implants. Using stacked spirals reduces the consumed space and the self-resonant frequency (SRF) of the spiral and the required power transmission frequency for the implanted device. A four-layer 15mm x 15mm spiral coil of seven turns is simulated in CST Microwave Studio (TM), constructed and tested in hardware with comparable results. Measurements also include the receipt of power inductively from an energised array of spirals powered by a Class-E transmitter at 27-MHz, and rectified to 1V for biosensor applications.

Index Terms—Stacked spirals, coils, wireless power transfer, inductive links, biomedical implants.

I. INTRODUCTION

THE design of electronic devices for biosensors presents a number of additional challenges compared with non-biological environments. Inductive links are a popular choice in this regard, in that their ability to power small implants and biosensors without the need for batteries or periodic surgery opens the opportunity to sense signals in more sensitive or physically restrictive areas of the body. However, size constraints present a significant design problem when designing such links.

Inductive links operate as weakly coupled transformers, where the external part of the transformer is the primary coil and the secondary coil is implanted in the patient [1]. The ‘core’ of this transformer is a combination of air and the human tissue that exists between the coils. In most cases this human tissue comprises of layers of skin, fat and muscle. Human tissue has electromagnetic properties that are frequency dependent. While the permittivity reduces with an increase in frequency, conductivity also increases, thus allowing the absorption of more energy [2]. Operating at lower frequencies avoids this problem, however this requires the use of larger inductors to transfer energy which presents a problem for smaller implants. As a result of the trend to miniaturise implantable devices, inductive links have been designed to operate at increasingly higher frequencies such that the spatial requirements of internal coils are reduced [3], [4], [5], [6].

A factor which also influences the spatial requirements of implantable coils is the type of inductive coils being used. Coupling between coils is enhanced when the turns of each coil are distributed across the radius rather than concentrating them at the outer radius of the coil [7]. Observing the field patterns of two coils of similar size and inductance but different shape illustrates this point. The z-component of the magnetic field of a cylindrical helix coil is shown in Fig. 1. The simulation result of a similar-sized Archimedean spiral coil is shown in Fig. 2. The field patterns of the spiral coil tend towards the blue and red ends of the scale indicating a much stronger field compared with the helix coil of Fig. 1. This implies that spiral coils will produce stronger coupling than cylindrical helix coils. However, the spatial requirements of planar Archimedean spirals compared with cylindrical helix coils of the same inductance are much greater. This presents the challenge of managing a trade-off between a larger spiral coil with a stronger magnetic field pattern, and a smaller cylindrical helix coil with a weaker magnetic field pattern.

Spiral and cylindrical helix inductors are modelled as dominantly inductive elements with smaller non-ideal elements, the most notable of which are the coil’s series resistance and parasitic capacitance [9]. The resistance exists due to the length, resistivity and cross sectional area of the coil’s conductor. The parasitic capacitance exists due to the close proximity of the several turns of conductors. Furthermore, the existence of parasitic capacitance implies that there exists a frequency at which the inductive and capacitive impedances of the coil match, or in other words a self-resonant frequency (SRF) [10]. The Q-factor of the coil approaches zero at this point, defined by $X/R$ where $X$ is reactance and $R$ is resistance. However the peak Q occurs below the SRF where the inductive reactance is dominant.

While spiral coils produce stronger field patterns, they require more space than cylindrical helix coils. The SRF of spiral coils is also much higher due to a smaller parasitic capacitance, in that conductors are separated much further from each other [9].

One possible solution to this problem is to construct a spiral to be a combination of several smaller spirals which are connected in series and stacked on top of each other, summing to equal the equivalent larger inductance value and ensuring that the flux lines of each layer point in the same direction [11]. The concept of stacking spiral inductors has been applied in integrated circuit technology mainly for the purpose of miniaturisation [12], [13], [14], [15]. An implantable stacked dipole antenna for data transfer in biomedical telemetry has also been used [16]. This paper studies the use of stacked spirals for inductive power links.

Stacking spiral inductors is advantageous specifically for the receipt of inductive power to power biosensors in telemetric systems. The parasitic capacitance of a stacked spiral inductor is likely to be greater due to the closer proximity of each spiral layer [9]. This significantly decreases the SRF of an implanted coil. This is advantageous because, as mentioned
in this section the human body undesirably absorbs more energy as the frequency of operation increases. It is therefore preferable to operate at lower frequencies and occupy less space for the wireless transfer of power. Another feature of operating at lower frequencies is that signals will propagate further. This potentially allows a greater range of transmission.

II. PARAMETRIC ANALYSIS

The hypothesis that stacking spirals would lower a coil’s SRF is investigated using the CST Microwave Studio\textsuperscript{TM}. In order to consider the effect of different variables on the SRF of a coil, it is necessary to consider the variables which affect a coil’s parasitic capacitance, \( C \). \( C \) is proportional to the electrical permittivity of a material between two conductors \( \varepsilon \), as is the area of conductors facing each other, \( A \). Capacitance is inversely proportional to the distance between the conductors, \( d \). These basic relationships summarised in (1) will be investigated in further detail with respect to stacked spiral antennas.

\[
\begin{align*}
C & \propto 1/d \\
C & \propto \varepsilon \\
C & \propto A
\end{align*}
\]

(1)

In order to observe the effect of stacking spirals, in addition to understanding the effect of certain parameters on SRF, a single square-spiral coil is initially simulated, measuring at 15mm x 15mm with seven 0.5mm wide turns on a piece of FR-4 board as shown in Fig.3.

A parametric sweep is conducted, where the effect of varying the FR-4 substrate’s thickness is compared for several SRF peaks. Given that for a single-layer spiral, parasitic capacitance exists between conductors on the same plane. Varying the thickness of the board substrate is not a direct variation of the distance \( d \) shown in (1), however it is an important practical variable to investigate. A plot of SRF peaks is presented in Fig.4, and it is evident that for thicknesses up to 1.5mm, variations in substrate thickness cause significant variation the capacitance and therefore SRF of the spiral. For thicknesses greater than this, variations in thickness have little effect on the spiral’s SRF in that the dielectric material acts as a half-space.

Based on (1), the electrical properties of the PCB substrate are likely to have an impact on the SRF of a stacked spiral. The parasitic capacitance is mainly proportional to the dielectric constant \( \varepsilon_r \) of a material that exists between any two conductors in the stacked spiral arrangement. The single-layer spiral of Fig.3 is simulated with relative permittivity \( \varepsilon_r \) ranging from 1 to 4.9. The results show that as \( \varepsilon_r \) of the material increases, the SRF peaks of the material decrease, and become more robust to the variations in \( \varepsilon_r \). FR-4 has an \( \varepsilon_r \) of 4.9 in CST Microwave Studio\textsuperscript{TM}.

The third parameter to observe from (1) is \( A \), which is the area of the conductors between which capacitance exists. This parameter may be viewed from many aspects, such as conductor thickness and track width, however the effect of stacking the spirals is of particular interest given that stacking spirals will increase the overall area between conductors.

Another spiral is added on the other side of the single layer spiral of Fig.3 to form a double spiral in order to observe the effect of increasing the area between layers. The simulation is further extended to two double layer spirals in an arrangement as shown shown in Fig.8 such that are four layers stacked on top of one another. The stacked spiral is created with two double-sided 1.5mm-thick FR-4 boards, and separated by a 1.5mm air gap, as shown. Fig.9 shows the stacked 4-layer spirals without the FR-4 boards visible. It illustrates how each spiral is oriented such that the direction of current creates magnetic flux lines that point in the same direction in a similar
The self-impedance of the spiral is shown in Fig.10. The plot shows the real component of the self impedance \( Re(Z_{1,1}) \) for the single spiral, double spiral, and the four-layer stacked spiral. The value of the peak impedance of the stacked spiral is higher than that of the single layer, which is expected in that the four-layer stack was in fact constructed by connecting four flat spirals electrically in series. The SRF of the single layer spiral is 1.04GHz, while the SRF of the four-layer stacked spiral is much lower, at 65 MHz. The number of peaks also increases as more spirals are stacked upon one another due to the varying capacitive elements and interactions between each layer.

Magnetic field patterns are also simulated at the peak frequency of both the single and multi-layer spiral coils, by taking a slice along the \( y \)-axis and viewing the strength of the \( z \)-component of the magnetic field. The simulation captures in Figs. 6 and 7 are both set on the same scale, and it is clear that the stacked spiral with the lower SRF is producing a greater range of field.

### III. Hardware Measurements

A stacked spiral identical to that of Fig.8 is constructed on FR-4 boards, with an SMA connector attached for measurement. A photo of the antenna is shown in Fig.12. It is measured with an Agilent Network Analyser E5071B, which provides the real and imaginary elements of the scattering parameter \( S_{1,1} \).

The \( S_{1,1} \) data is converted to real and imaginary elements of \( Z_{1,1} \) using (2) and (3) \( \left( Z_0 = 50 \Omega \right) \). Fig.11 shows the measured \( Re(Z_{1,1}) \) along with an overlaid plot of the associated simulation result from CST Microwave Studio™.

\[
Re(Z_{1,1}) = Z_0 \frac{1 - Re(S_{1,1})^2 - Im(S_{1,1})^2}{Re(S_{1,1})^2 - 2Re(S_{1,1}) + Im(S_{1,1})^2 + 1} \tag{2}
\]

\[
Im(Z_{1,1}) = Z_0 \frac{2Im(S_{1,1})}{Re(S_{1,1})^2 - 2Re(S_{1,1}) + Im(S_{1,1})^2 + 1} \tag{3}
\]

A comparison of the two plots shows that the simulation and measured results for the four-layer stacked spiral are in reasonable agreement. There is however some variance between the frequencies of some of the peaks. The lowest frequency at which a peak occurs is around 30 MHz, compared with the simulated frequency of 65 MHz. These deviations are as expected, in that the stacked spiral was simulated without the presence of the SMA connector or any other objects around it, which may contribute additional capacitance. It is also important to note that for practical applications, surrounding tissue, circuit models and proper insulation layers must be considered based on the specific use of the implant.

#### A. Receiving Wireless Power

The stacked spiral is used to receive power wirelessly from a plane of several small spirals organised in cells and connected in an array as shown in Fig.13. It is fixed 25mm above the energised base, with air being the medium of transmission. The intended application for this experimental setup is preclinical testing, where the subject is enclosed in a tank, free to move about this surface while the stacked spiral, along with other electronics, is implanted [8].

The circuit used to energise the base is a Class-E amplifier which is a popular power amplifier used to transmit wireless energy through inductors at high frequencies [18] [19]. Its popularity lays in its ability to avoid switching losses at high frequencies, allowing higher efficiency transmission at these frequencies. It has been used frequently in biomedical applications, where the need for high efficiency and high frequency operation is important [20] [21] [4].

The Class-E amplifier circuit, shown in Fig.14 consists of an oscillating input signal, a transistor \( M \), choke inductor \( L_1 \), Capacitors \( C_1 \) and \( C_2 \). The element \( L_2 \) represents the inductive spiral array shown in Fig.13. A parasitic capacitance element also exists in parallel with \( L_2 \), however its significance to the operation of the Class-E circuit depends on the frequency of operation [8].

The circuit is supplied by a 9V DC supply, and designed to transmit energy at the ISM frequency of 27-MHz using an ABRACON-ACHL-27MHZ-EK oscillator as the input signal. This frequency is used because it belongs within the bandwidth of the stacked spiral antenna, and it is also within an ISM band. \( M \) is an n-channel MOSFET NDC7001C from Fairchild.

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**Fig. 4.** Simulation results showing peak frequencies of the antenna shown in Fig.3 as the FR-4 substrate thickness varies.

**Fig. 5.** Simulation results of the single layer spiral of Fig.3 showing peak frequencies as the relative permeability \( \varepsilon_r \) is varied.
Fig. 6. A simulation of the $z$-component of the magnetic field pattern of the single layer coil in Fig.3 at its SRF of 1.044GHz. The scale ranges from $\pm10\text{A/m}$.

Fig. 7. A simulation of the $z$-component of the magnetic field pattern of the multi layer coil in Fig.8 at its SRF of 65MHz. The scale ranges from $\pm10\text{A/m}$.

Fig. 8. An image of a simulated four-layer spiral coil, comprising four coils covering 1.5mm x 1.5mm with 7-turns of 0.5mm thick conductors, separated by two 1.5mm FR-4 boards.

Fig. 9. An image of the simulated four-layer spiral coil of Fig.8, with the FR-4 layer switched to transparent, allowing the conductors throughout the stacked-spiral to be visualised.

Fig. 10. A comparison between the simulated $Re(Z_{1,1})$ curves for a single square spiral, double layer spiral and a 4-layer stacked spiral.
Fig. 11. A comparison between the simulated and measured results of the frequency vs real impedance $\text{Re}(Z_{11})$ plot.

Fig. 12. A photograph of a four layer spiral coil.

Fig. 13. A photo of the stacked spiral antenna receiving energy from a Class-E powered spiral array.

Fig. 14. Wireless power transfer with class-E amplifier.

Semiconductor, $C_1$ is 109pF and $C_2$ is 4.7pF. The antenna array comprises 20 printed copper spirals, each 100mm x 100mm with 7 turns each. As shown in Fig.13, each column of five spirals are connected in parallel, and the four columns are connected in series. The coils are printed on an FR-4 substrate with a 1.5mm thickness.

Fig.15 shows the voltage waveform across the transmitter and Fig.16 shows the received signal on the stacked spiral inductor with a high impedance $1M\Omega$ probe. The transmitted and received power spectrums are presented in Figs.17 and 18 respectively. Of the transmitted power of $6dBm$, $-27dBm$ is received. The received power signal was rectified to 1V as shown in Fig. 19 using a diode and $10\mu F$ capacitor. This is enough to power most biosensors and current IC technology [22], [23], [24].
IV. DISCUSSION

The results of this investigation show that stacking spirals presents several advantages in the context of bio-implantable devices, where space and high frequency absorption are two major concerns.

Section I mentioned that spiral coils produce stronger field patterns than cylindrical helix coils, and that they require more space for the equivalent inductance. Stacking spirals above one another allows the miniaturisation of the equivalent one-layer flat spiral. The stacked spirals are also more space efficient than their equivalent cylindrical helix coils in that more conductor length can be utilised in the same volume, leaving no hollow gaps as shown in Fig.9.

Miniaturisation is also significant in the context of transmission frequency for implantable devices. The fact that a higher inductance coil may be produced in a smaller volume means that a lower frequency of transmission is possible. It is also interesting to note that coils with similar frequency properties may be scaled to even smaller sizes, ensuring that the inductance $L$ and parasitic capacitance $C$ resonate at the correct frequency. If equivalent inductance is desired, less turns per square $mm$ are required [10].

The third interesting effect of stacking spiral coils is the reduction of a coil’s SRF. Due to the fact that multiple layers of stacked spirals are in close proximity to one another the layers also act as capacitors, increasing the equivalent parasitic capacitance of the spiral. This reduces the overall SRF and hence the operational frequency required for the wireless transmission of power, which is advantageous in the biological environment. The reduction of operational frequency also increases the transmission range for the coil due to the larger wavelength and less absorption.

The stacked spiral was used to receive energy from an energised array of spirals, and -27dBm was the measured level of power on the stacked spiral from a transmission of 6dBm 25mm away.

V. CONCLUSION

Size is an important consideration in electronic devices for biosensors. It is more efficient to transmit inductive power
at lower frequencies. While cylindrical helix spirals are commonly used for implantable devices, spiral coils produce better field patterns. A parametric analysis has been conducted on the spiral coils, showing the sensitivity of variations in board thickness, dielectric constant and surface area on SRF peaks. By stacking several spirals on top of one another, the space required for an implantable coil has been miniaturised, and the SRF of the spiral is reduced. Moreover, the power transmission frequency for the implanted device is reduced, which is advantageous in the context of bio-implantable devices. The results of simulations and a hardware implementation for a four-layer 15mm x 15mm spiral coil of seven turns are successful in demonstrating these effects. Power was transmitted to the stacked spiral from an energised array of spiral cells at 27-MHz, and was received and rectified successfully at a level suitable for biosensor applications.

REFERENCES


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