Stacked Spirals for Use in Biomedical Implants

Anthony N. Laskovski, Mehmet R. Yuce, Tharaka Dissanayake

*School of Electrical Engineering and Computer Science, The University of Newcastle
University Drive, Callaghan NSW 2308 Australia*

¹alasko@ieee.org

²Mehmet.Yuce@newcastle.edu.au

³Tharaka.Dissanayake@newcastle.edu.au

Abstract—A new type of wireless transmission coil is proposed for biomedical implants. By stacking several spirals above one another, the space required for an implantable coil is miniaturised, the self-resonant frequency (SRF) of the spiral is reduced, as is the required power transmission frequency for the implanted device. A four-layer 15mm x 15mm spiral coil of seven turns was simulated in CST Microwave Studio (TM), and constructed and successfully tested in hardware.

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

I. INTRODUCTION

Inductive links are used to supply power to bio-implantable electronic devices. Their ability to power small implants without the need for batteries or periodic surgery opens up the opportunity to implant devices into more sensitive or physically restrictive areas of the body. Inductive links operate as weakly coupled transformers, where the external part of the transformer is the primary 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, the conductivity also increases, thus allowing the absorption of more energy [2]. Operating at lower frequencies avoids this problem, however this requires larger inductors to transfer energy and it presents a problem in for smaller implants. As a result of the trend to miniaturise implantable devices, inductive links have been designed to operate at increasing frequencies so that the spatial requirements of internal coils are reduced [3] [4] [5] [6].

A factor which also influences the spacial requirements of implantable coils is the type of inductive coils being used. Coupling between coils is enhanced when turns of the coil are distributed across the radii rather than concentrating them at the outer radius of the coil [7]. This implies that spiral coils such as the one shown in Fig. 1 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 requires the consideration of 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.

Fig. 1. A screenshot of a one layer square spiral simulation

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 [8]. The resistance exists due to the length, resistivity and cross sectional area of the coil's conductor, and 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 imaginary impedance is zero, or in other words a self-resonant frequency (SRF) [9].

The SRF of an inductive coil becomes a significant consideration in designing radio frequency (RF) electronic circuits to drive or receive signals through the coil. One such example may be seen in the Class-E amplifier, which is a popular power amplifier used to transmit wireless energy through an inductor at high frequencies [10] [11]. Its popularity lays in its ability to avoid switching losses at high frequencies, allowing higher efficiency transmission at these frequencies. However, at operational frequencies above 100 MHz, the parasitic capacitance of a Class-E amplifier's constituent coil inductor becomes comparable to the prescribed discrete capacitor values in the circuit itself (in the order of 10s of pF), and it changes the resonance of the circuit, altering its SRF.

The simplified expression for the resonant frequency of the Class-E circuit, ω , is shown in (1), where L_2 represents an inductive coil and C_1 and C_2 are two prescribed capacitors in the amplifier. The additional term C_3 , which is not usually included, was added to this equation and shown in (1). This represents the parasitic capacitance of the inductive coil L_2 .

Fig. 2. A Class-E amplifier

$$\omega = \frac{1}{\sqrt{L_2(C_1 || C_2 + C_3)}} \quad (1)$$

An observation of (1) indicates that a variation in a coil's parasitic capacitance C_3 affects the resonance of the Class-E amplifier more than variations in the circuit's prescribed capacitors C_1 and C_2 . Given that at higher frequencies the values of C_1 and C_2 are in the same order of magnitude as the parasitic capacitance C_3 , it is fair to say that the self resonant frequency of a spiral plays a significant role in the RF electronic circuit in which it is connected.

II. STACKED SPIRALS

Section I mentioned a comparison between spiral coils and cylindrical helix coils, stating that 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 [8].

One possible solution to this problem is to create one larger spiral as 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. The concept of stacking spirals has been applied in integrated circuit technology mainly for the purpose of miniaturisation [12] [13].

While miniaturisation by stacking spirals is also advantageous in the context of bio-implantable electronic devices, there are other effects which make this concept advantageous for the biological environment. The parasitic capacitance of a stacked spiral coil is likely to be greater due to the closer proximity of each spiral layer [8]. This could significantly decrease the SRF of an implanted coil that serves the purpose of receiving power from the primary transmitting coil external to the body. This is advantageous in that, as mentioned in Section I, the human body undesirably absorbs more energy as the frequency of operation increases and it is preferable for the wireless transfer of power to operate at lower frequencies and occupy less space. Operating at lower frequencies also allows signals to propagate further, enabling a greater transmission range.

Spiral stacking also increases the inductance which can be implemented in a given space, which allows more energy to be transmitted or received on such coils.

Fig. 3. 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. 4. An image of the simulated four-layer spiral coil of Fig. 3, with the FR-4 layer switched to transparent, allowing the conductors throughout the stacked-spiral to be visualised.

III. SIMULATION RESULTS

A single square-spiral coil was simulated in CST Microwave Studio (TM), measuring at 15mm x 15mm, with seven 0.5mm wide turns on a piece of 1.5mm thick FR-4 board as shown in Fig. 1.

A stacked spiral was also implemented in simulations by stacking spirals such as the one shown in Fig. 1 to form a four-layer stack. The stacked spiral was created with two double-sided 1.5mm thick FR-4 boards, and separated by a 1.5mm air gap with seven turns, as shown in Fig. 3. Fig. 4 shows the stacked 4-layer spirals without the FR-4 boards visible, in order to illustrate that each spiral was oriented on its respective layer such that the direction of current in the spiral would ensure that the magnetic flux lines pointed in the same direction, similar to [14].

The self-impedance of the spiral was produced and shown as $|Z_{1,1}|$ in Fig. 5. One plot shows the $|Z_{1,1}|$ parameter for the single spiral, while the other shows $|Z_{1,1}|$ for the four-layer stacked spiral. The value of the peak impedance of the stacked spiral was significantly higher than that of the single layer, which was 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 was 1.04GHz, while the SRF of the four-layer stacked spiral was much lower, at 65 MHz.

Magnetic field patterns were 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 plots in Figs. 6 and 7 are both set on the same scale, and it is clear that the stacked

Fig. 5. A comparison between the simulated $Re(Z_{1,1})$ curves for a single square spiral and a 4-layer stacked spiral

Fig. 6. A simulation of the z -component of the magnetic field pattern of the single layer coil in Fig. 1 at its SRF of 1.044GHz. The scale ranges from ± 10 A/m

spiral with the lower SRF is producing a greater range of field.

IV. HARDWARE MEASUREMENTS

A stacked spiral identical to that of Fig. 3 was constructed on FR-4 board, with an SMA connector attached for measurement. A photo of the antenna is shown in Fig. 8. It was measured with an Agilent Network Analyser E5071B, which provided the real and imaginary elements of the scattering parameter $S_{1,1}$.

The $S_{1,1}$ data was converted to real and imaginary elements of $Z_{1,1}$ using (2) and (3). Fig. 9 shows the measured $Re(Z_{1,1})$ along with an overlaid plot of the associated simulation result from CST Microwave Studio (TM).

$$Re(Z_{1,1}) = Z_o \frac{1 - Re(S_{1,1})^2 - Im(S_{1,1})^2}{Re(S_{1,1})^2 - 2Re(S_{1,1}) + Im(S_{1,1})^2 + 1} \quad (2)$$

$$Im(Z_{1,1}) = Z_o \frac{2Im(S_{1,1})}{Re(S_{1,1})^2 - 2Re(S_{1,1}) + Im(S_{1,1})^2 + 1} \quad (3)$$

Fig. 7. A simulation of the z -component of the magnetic field pattern of the multi layer coil in Fig. 3 at its SRF of 65MHz. The scale ranges from ± 10 A/m

Fig. 8. A photograph of a four layer spiral coil

A comparison of the two plots shows that the simulation and measured results for the four-layer stacked spiral are in reasonable agreement. There was however some variance between the frequencies of some of the peaks. The lowest frequency at which a peak occurred was 30 MHz, compared with the simulated frequency of 65 MHz. These deviations were as expected, in that the stacked spiral was simulated without the presence of the SMA connector or any other objects around it, which may have contributed 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.

V. DISCUSSION

The results of this investigation show that stacking spirals for antenna 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,

Fig. 9. A comparison between the simulated and measured results of the frequency vs real impedance $\text{Re}(Z_{11})$ plot

leaving no hollow gaps as shown in Fig. 4.

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.

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.

VI. CONCLUSION

Bio-implantable electronic devices are required to be as small as possible, and it is preferable to transmit power inductively at lower frequencies. While cylindrical helix spirals are commonly used for implantable devices, spiral coils produce better field patterns. By stacking several spirals on top of one another, the space required for an implantable coil has been miniaturised, the SRF of the spiral is reduced, and 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 were successful in demonstrating these effects.

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