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High-Efficiency Wireless Power Delivery for Medical Implants Using Hybrid Coils

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***Abstract*— With the exciting developments in the implant technology allowing sophisticated signal processing, stimulation, and drug delivery capabilities, there is new hope for many patients of epilepsy, Parkinson's disease, and stroke to improve their quality of life. Such implants require high power to deliver the promised rich functionality. Yet, delivering high power to implants without damaging the tissue due to heating while keeping the implant footprint small is a challenge. In this paper, we propose a hybrid multi-layer coil as the secondary coil to provide a power and space-efficient solution. The proposed coils can deliver power to an implant for long durations without increasing the skin temperature over 1C.**

I. Introduction

Efficiency of wireless power link is a critical factor in the design of robust implants, since, if not carefully designed, the loss on these links can contribute to excessive heating, which can cause skin tissue damage [1]. On the other hand, to sustain the next generation implants with on-line and complicated circuits such as online seizure detection circuits [2], [3], it is a necessity to deliver large amount of power to these implants. Adding the strict constraints on the space available to the implant devices on top of the trade-off between high-power delivery requirement and the safety of biological tissue, the design of efficient coils for the wireless power links poses a challenge.

Planar spiral coil (PSC) offers remarkable features such as design control, output power, and compact size for wireless power transmission. There are numerous design approaches hitherto, for spiral coils like solenoid type [4], [5], and printed spiral coils [6].

For efficient power transmission, especially for biomedical implant devices where there are strict form factor restrictions, litz wire PSC design suits well.

We recently proposed [7] multi-layer coils for safe wireless power transmission for medical implants, where rather than enlarging the coil diameter, we proposed to have layers of coils stacked together providing a high-power efficiency in a limited amount of space.

In this paper, we propose hybrid multi-layer coils , which consists of layers of full and hollows coils (pictured in Fig. 1). The proposed approach improves the multi-layer coils by allowing more layers of coils to stack up and thus getting higher efficiency using the same coil diameter.

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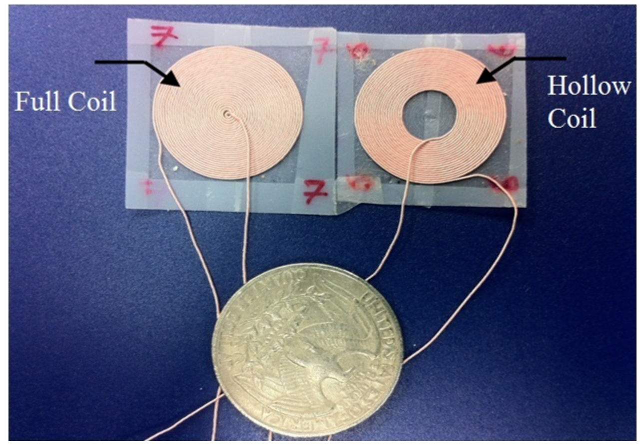

Fig. 1. Full and hollow type of coils for hybrid coil configuration.

We show that by using the proposed coils, a sustained 80 mW power can be delivered to a load continuously without increasing the skin temperature over 1°C.

The rest of the paper is organized as follows: In Section II, the analytical equations representing the power efficiency of the wireless links are summarized. In Section III, the proposed hybrid multi-layer coil structure is presented. Section IV demonstrates the performance of the hybrid multi-layer coils with experiment results. Section V concludes the paper.

II. Power Efficiency of a Wireless Link

The power efficiency of a wireless link can be defined as [6]

$$\eta = \frac{k^2 \cdot Q_1 \cdot Q_L}{1 + k^2 \cdot Q_1 \cdot Q_L} \times \frac{Q_2}{Q_2 + Q_L} \qquad (1)$$

where k is the coupling coefficient between the two coils, Q_1 and Q_2 are the quality factors of the coils, and Q_L is the quality factor of the loaded secondary coil.

The coupling coefficient between two coils is given as follows

$$k = \frac{M}{\sqrt{L_1 . L_2}} \qquad (2)$$

M is mutual coupling between primary and secondary coil. The quality factor for the coils can be given as

$$Q = \frac{\omega \cdot L - \omega(R_{ac}^2 + \omega^2 \cdot L^2) \cdot C_P}{R_{ac}} \approx \frac{\omega \cdot L}{R_{ac}} \qquad (3)$$

where the approximation is valid for small values of C_P and at resonance frequency ω_0, for a capacitance of C_2 in the secondary resonant circuit and a load resistance of R_L, Q_L can be given as [6], [8],

$$Q_L = \frac{1}{\frac{R_{S2}}{\omega \cdot L_2} + \frac{\omega \cdot L_2}{R_L}} = \frac{1}{R_{S2} \cdot \sqrt{\frac{C_2}{L_2}} + \frac{1}{R_L} \cdot \sqrt{\frac{L_2}{C_2}}} = \omega_0 \cdot R_L \cdot C_2 \tag{4}$$

The mutual coupling, M, and thus the coupling coefficient k strongly depend on the distance and misalignment between coils and is the determining factor for the first term in (1) for a given Q_1. Increasing the secondary coil quality factor, Q_2 will increase the secondary term in (1) and thus also increase the wireless link efficiency. In the rest of this section, we focus on investigating the factors affecting Q_2, and design the proposed coils to maximize Q_2. In particular, we investigate the R_{ac} of the secondary coil, which is also the main factor limiting the Q_2 as shown in (3). The R_{ac} is the representation of the ohmic losses in a coil, which consists of (1) the DC resistance of the coil, R_{dc}, (2) the losses due to bundle twisting for wires with multiple strands, (3) the losses due to skin effect, (4) the losses due to the proximity effect, and (5) the losses due to displacement current.

A. Power Loss Considerations

1) DC Resistance: The DC resistance of a coil wound from a wire with N_s strands can be given as [9]

$$R_{dc} = \frac{l}{\sigma \pi r_s^2 N_s} \left[1 + \frac{\pi^2 r_s^2 N_s}{K_a p^2} \right] \tag{5}$$

where σ is the conductivity of the conductor, l is the length of the wire, and r_s is the radius of each strand. The term in the bracket is due to the effective length increase of the strands as a results of twisting the bundle, where p is the pitch of twisting and K_a is the packing factor. The packing factor is the ratio between the sum of cross sectional area of each strands of bundle to the total cross sectional area of bundle [10].

2) Skin Effect Loss: As the operating frequency increases, the current confines itself over the surface of the conductor reducing the effective conductor area of signal propagation to a narrow range defined by the skin depth, δ, of the conductor, which can be written as

$$\delta = \sqrt{\frac{2}{\mu_0 \sigma \omega}} \tag{6}$$

The μ_0 is the permeability of the conductor. This confinement of the current to the conductor surface is known as skin effect and it increases the conductor resistance.

General equation of tbe resistance due to skin effect for a round conductor is given in [11] in terms of Kelvin (Bessel) functions. For thin conductors such as the Litz wire, since the radius of a strand, $r_s \leqslant \delta$, this equation can be simplified as follows:

$$R_{skin} = R_{dc} \left[1 + \frac{r_s^4}{48 \delta^4} \right] \tag{7}$$

3) Proximity Effect Loss: Power loss owing to proximity effect is a major one in Litz wire wound coils. This is an inherent effect due to bunch and strands inside the bunch being in too close proximity of each other. The total proximity loss can be analytically solved and its relation to R_{ac} can be derived. A simplified version of this relation is given in [4].

4) Displacement current effect: Due to bunch strands and bundle itself being very closely spaced across the whole winding, parasitic capacitive effects exist. Between every single turn of the coil a tiny finite gap results into exchange of charge through air as dielectric media. This phenomena further increases already dominant AC resistance, and is called as Effective Series Resistance (ESR) [4].

Since all the contributors to the AC resistance is covered, we can define R_{ac} that incorporates the effects of all these contributors. The AC resistance can be given as [4]

$$R_{ac} = R_{dc} \left(1 + \frac{f^2}{f_h^2} \right) \text{ with } f_h = \frac{2\sqrt{2}}{\pi r_s^2 \mu_0 \sigma \sqrt{N_t N_s \eta \beta}} \tag{8}$$

$$R_{ac} = R_{dc} \left[1 + \frac{f^2 (\pi r_s^2 \mu_0 \sigma)^2 (N_t N_s \eta \beta)}{8} \right] \tag{9}$$

where η is geometry dependent parameter, β is area efficiency, N_t is total number of turns.

$$ESR = \frac{R_{ac}}{(1 - 4\pi^2 f^2 L C_{self})^2} \tag{10}$$

Capacitance of a single-layer coil can be given as

$$C_{self} = \sum_{p<k} \left(\frac{C_{p,k} \cdot (k-p)^2}{N_t^2} \right) \tag{11}$$

where $C_{p,k}$ is the capacitance between the turns p, and k [4].

R_{ac} has nonlinear dependency on frequency and on various geometrical parameters, which makes it hard to optimize. Yet, keeping R_{ac} low is crucial to have a power link efficiency since it is the main factor to deteriorate the quality factor. It is necessary to take into account the skin effect, proximity effect, and displacement current effects for proper design of multi-layer coils. Though, at higher frequencies skin effect related losses are less pronounced with respect to the proximity losses, skin effect related losses cannot be neglected. In the following subsections, we will explore their significance for Litz wire stacked coils.

III. Hybrid Multi-Layer Coils

The multi-layer coils can provide a space and power-efficient solution to the design of secondary coils for the wireless power links in the medical implants [7]. However, although increasing number of layers can boost the performance up to a certain degree, the number of layers that can be added for a specific coil geometry is limited since beyond a certain number of layers, the performance starts to degrade rapidly.

In this paper, we propose hybrid multi-layer coils to improve the scalability of multi-layer coils to higher number of layers while sustaining an increase in power efficiency. As in the multi-layer coils, the hybrid multi-layer coils also does not enlarge the outer diameter of the coils, thus provide a space-efficient design. In this section, we outline the proposed hybrid multi-layer coils and the motivation behind using these coils for efficient power transmission.

A single layer planar spiral coil (PSC) can be designed to have a fairly high quality factor (Q), but its energy density is poor owing to its relatively small self-inductance (L). To increase L, there are primarily two options for a given coil structure, (1) increase the number of turns, and (2) stack more layers. The first option has the disadvantage of enlarging the outer diameter of the coil. Since, in medical implants, the area of the coil is highly constrained, this is not preferred. The second option provides similar benefits, yet by only slightly increasing the thickness of the coil without changing its outer diameter (*i.e.,* surface area of the coil stays the same).

As more layers are added to a PSC stack (multi-layer coil), its energy density increases due to the increase in the value of the self inductance (Fig. 2). Stacking more layers, also increases the Q for a given multi-layer coil. It was shown in [7] that four layer PSC offers the highest power efficiency. As stacking goes beyond four layers though, the increase in R_{ac} becomes faster than the increase in L for that stack. The rapid rise of the R_{ac} value deteriorate the Q value (Eq. (3)) that finally severely impacts efficiency of power transmission.

Since multi-layer coils power efficiency increase cannot scale with added layers after certain amount of layers due to the rapid increase of R_{ac}, we investigate potential ways to improve the scalability of multi-layer coils so that more layers are added to increase power efficiency. The coils used in [7] are full coils, *i.e.,* their inner diameter is close to 0. It is well-known that by removing turns from inside the coil, coils with smaller R_{ac} can be achieved. In this paper, we call such coils as hollow coils (*i.e.,* coils with an inner diameter $d_i \gg 0$) have smaller R_{ac}, since the inner turns contribute significantly to R_{ac}. However, these coils also have smaller L thus their energy density is lower.

In this paper, we take an alternate approach, where we stack a full coil, with a set of hollow coils. We call this setup as hybrid multi-layer coils. The hybrid multi-layer coils combines the advantages of both hollow and full coils. By having a full coil, the hybrid multi-layer coils still has higher L compared to the hollow coils, whereas its R_{ac} is much smaller compared to a full multi-layer coils thanks to the low R_{ac} hollow coils in the stack. This allows further increase of number of layers while sustaining the increase in power efficiency using hybrid multi-layer coils. In the next section, we demonstrate the hybrid multi-layer coils performance.

IV. Results and Discussions

In this section, we first show the measured electrical parameters of hybrid coils with different number of layers, and compare these parameters to the parameters of multi-layer coils. Then, we provide results of our experiments using these coils on a wireless power link for the heating impact of the link to the biological tissue. In particular, experiments have carried out to determine how long a wireless power link can deliver a pre-determined power to a load without exceeding the allowed temperature increase for medical implants (*e.g.,* no more than 1 or $2°C$) using the proposed coils. In our setup, a Class-E amplifier [12] is used to drive the primary coil ($L_1 = 19$ μH, $Q_1 = 67$) at a resonant frequency of 1 MHz, which is also the resonant frequency for the secondary. A hybrid secondary coil is designed as follows, a stack of multi-layer hollow coils with a diameter of 2 cm, and 20 turns is stacked on a single layer full coil with a diameter of 2 cm and 30 turns. The performance of this hybrid coil is compared with the 4-layer multi-layer coil, the best performing multi-layer coil in [7]. The performance is measured when delivering a fixed power (80 mW) to a fixed load of 20 Ω. A 1 cm thick slab of porcine meat (consisting of skin, fat and muscle tissues) is used in between the primary and the secondary coil to evaluate the heating effects of the wireless link on the biological tissue. Further details of the test setup, the properties of the primary coil, and the preparation of the porcine meat for the experiments were similar to our previous test setup and already reported in [7].

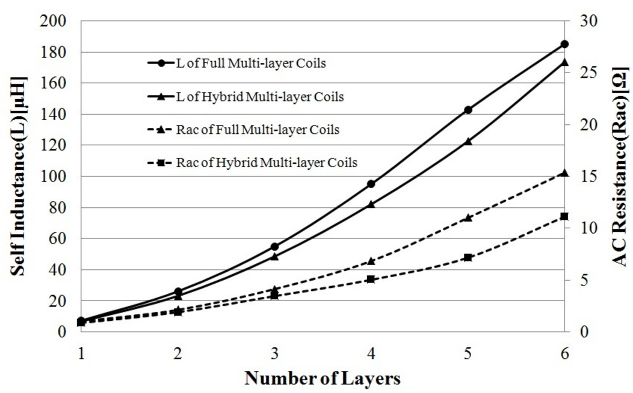

Fig. 2. Measurement results comparing the self inductance (L) and AC resistance R_{ac} of full and hybrid multi-layer coils.

In Fig. 2, the self inductance (L) and AC resistance (R_{ac}) measurements of the full and hybrid multi-layer coils are compared at 1 MHz using an HP4194A Impedance Analyzer. Both coils have the same diameter of 2 cm and for both coils the increase in L is higher than the decrease in R_{ac} as number of layers increase for up to 4 layers.

The degradation of self-inductance and the decrease in the AC resistance of the hybrid multi-layer coils with respect to the full coils are relatively small when number of layers is no more than 3. However, as the number of layers increases, the reduction in AC resistance becomes significant, whereas the degradation in L stays relatively small. In particular, the maximum relative difference of L for the same number of layers occurs for 4 layers. R_{ac} resistance is the primary parameter driving the losses high in the coils, and for hybrid multi-layer coils , the R_{ac} reduces significantly. Especially for 4- and 5-layer hybrid multi-layer coils, it can be deduced that R_{ac} is remarkably reduced by $30 - 40\%$ compared to the full multi-layer coil's R_{ac} value.

This in turn boosts the quality factor (Q) of the hybrid multi-layer coils as shown in Fig. 3 with respect to the full multi-layer coils. As reported in [7], due to the decline in Q, the increase in efficiency stops at 5 layers for full multi-layer coils. By introducing the hybrid multi-layer coils, the Q value is 15% higher in hybrid multi-layer coils with respect to full multi-layer coils, and also the Q stays high even for the 6-layer design, providing the best performance for preventing skin heating at 5 layers as shown below.

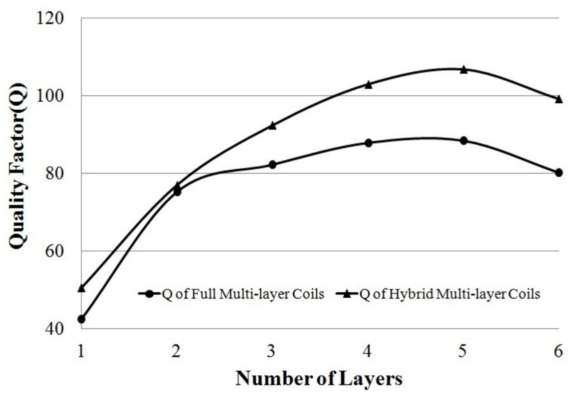

Fig. 3. Measurement results comparing the quality factor (Q) and AC resistance R_{ac} of full and hybrid multi-layer coils.

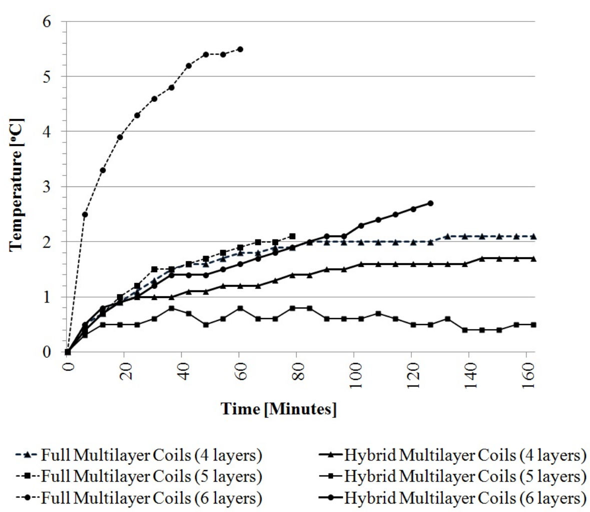

Fig. 4. Increase in the temperature of the 1-cm-thick porcine tissue in between primary and secondary coils in the wireless link for different full and hybrid multi-layer coils as secondary coil.

Fig. 4 compares the increase in the temperature of the porcine tissue in between the primary and the secondary coils using multi-layer coils and hybrid multi-layer coils as the secondary coil. For full multi-layer coils, the best performance is shown when number of layers is four, and the meat temperature does not exceed 2°C for over 2 hours, whereas the performance deteriorates as more layers added (5 or 6-layer). In particular, the performance with a 6-layer coil deteriorates the most. On the other hand, the hybrid multi-layer coils outperforms the full multi-layer coils, where 4-layer hybrid multi-layer coil stay below the 2°C mark much longer than the 4-layer full multi-layer coil. More remarkably, if a 5-layer hybrid multi-layer coil is used, the temperature rise stay below 1°C for the duration of the 160 minute experiment. This shows that proposed hybrid multi-layer coils can keep a wireless power link for long durations for instance to charge an implanted rechargeable battery, or running a high-power task without any harm on skin tissue since the temperature increase in the tissue stays within the allowed limits.

V. Conclusions

Wireless power links are crucial for the success of next generation chronic implants with advanced functionality. In this paper, we propose hybrid multi-layer coils as the secondary coil to boost the power-efficiency of these links. We show that using the proposed coils 80 mW power can be delivered to an implanted load safely for a long term, while keeping the tissue temperature increase to less than 1°C. Furthermore, this is achieved by keeping the outer diameter of the coil same, but only slightly increasing its thickness.

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