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Multi-Layer Coils for Efficient Transcutaneous Power Transfer

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***Abstract*— TETS (Transcutaneous Energy Transfer System) has been successfully used for powering medical implants for different purposes such as for neural recordings and drug delivery. Yet, due to their low power transfer efficiency, these devices can cause unacceptable increase in skin temperature limiting their scalability to high power levels. Although, the efficiency of these systems can be improved by increasing coil diameter, in many cases this is not practical due to strict physical constraints on the coil diameter. In this paper, we investigate using multi-layer coils as secondary coils in the TETS to increase the power transfer efficiency, and thus allowing the delivery of the desired power safely for a longer period. Our experiments show a 5x increase in the duration of safe power delivery (not increasing the skin temperature more than 2 C) using multi-layer coils as the secondary coil compared to using single-layer coils even when there is a 50% misalignment in between primary and secondary coils. This increase in duration of safe power transfer is shown to be over 16x more when the coils are aligned. The improvement in the duration of safe power transfer is achieved without increasing the coil diameter and with a coil thickness of 2 mm.**

I. Introduction

TETS (Transcutaneous Energy Transfer System) is crucial for powering medical implants for many applications such as neural recordings [1], drug delivery [2], and neurostimulators [3]. A major problem in the TETS is their low power transfer efficiency. An important contributor to this problem is the extreme constraints on the geometry of the primary and the implanted coils, although the constraints for the latter are usually more strict. The low power transfer efficiency causes skin heating and limits the maximum power that can be delivered to an implant, safely. This heating only becomes worse as the secondary coil moves, causing misalignment in between coils. Implanted batteries, which free the patient from carrying an external power supply at all times, require instantaneous transmission of high power during battery charging and may possibly stress the skin with high temperature rises in extreme cases. Though, high-performance battery chargers [4] exist, which minimize the duration of this high power transmission.

Whether the implant is directly powered with a TETS or the implant power is supplied by implanted batteries, which are recharged by TETS, it is beneficial to reduce the impact of such implants on the skin temperature by having a more efficient TETS.

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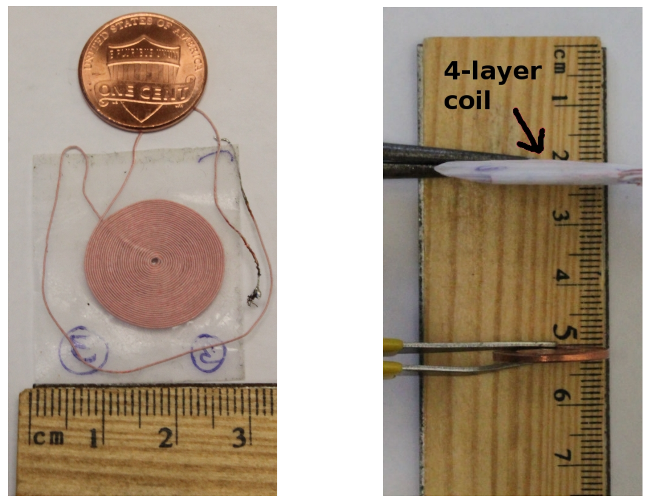

(a) (b)

Fig. 1: Single and multi-layer coils for the implants. (a) A single-layer coil wound from Litz wire with a diameter of 20 mm, and 30 turns next to the US Penny (diameter: 19.05 mm). (b) A 4-layer coil (white) viewed from the top (thickness: 2 mm including the surrounding tape) shown with the US Penny (thickness of 1.55 mm) for comparison.

Typically, a TETS should deliver up to a maximum power to an implant (load power) for a certain duration of time to complete a certain task successfully (*e.g.,* to deliver a drug, read and transmit sensor data, or recharge an implanted battery). Usually, based on the target application, the surface area of the implanted coil (and possibly the area of the primary coil) is limited. In such a setting, a reasonable question to ask would be *how long a specified amount of power can be delivered to the implant transcutaneously without heating the skin beyond the safety margin?*

Increase in the skin temperature beyond 1^oC or 2^oC for excessive time is considered unsafe. Obviously, as the power efficiency of the transcutanous link increases, the amount of energy contributed to the skin heating will be lesser for the same power delivered to the implant. In other words, more power can be delivered to a load for the same duration while still staying within the skin temperature safety margin, or equally we can prolong the time allowed for a procedure without compromising safety.

In this paper, we investigate coil structures to increase the power transfer efficiency and thus to reduce heating of the skin. In particular, we investigate the extend we can increase the duration of power delivery to an implant by replacing the single-layer coil in the secondary with a multi-layer coil with the same diameter, and without causing an unacceptable increase in skin temperature. We show that if a 4-layer coil is used as the secondary coil in a TETS instead of a single-layer coil, the duration of safe power delivery (not increasing the skin temperature more than 2^oC) increases 5 times even when there is a 50% misalignment in between primary and secondary coils. The increase in duration of safe power transfer is over 16 times more when the coils are aligned. This improvement in the duration of the safe power transfer is achieved without increasing the diameter of the coils, and with a coil thickness of 2 mm including the surrounding tape as shown in Fig. 1b.

The rest of this paper is organized as follows. Section II summarizes the recent related work in TETS. The design of the multi-layer coils is given in Section III. Section IV summarizes our experiment setup and results achieved. Section V concludes the paper.

II. Related Work

Design of coils for TETS has been thoroughly investigated [1], [2], [5]–[7]. In this section, we briefly summarize the related work with a focus on what we call in this paper as *aggregated coil structures* where either coils are wound with multiple strand Litz wire [5], or with strands made of multiple wires [6], or as is the subject of this paper, coils consisting of multiple layers (*i.e.,* stacked coils) [2], [7].

In their elaborate work [5], Yang *et al.* provide close-form equations for characterizing coils by taking into consideration the displacement currents. They reported that their model accurately matches measurement results up to 3.5 MHz and beyond. They also provided detailed trade-offs for design parameters such as number of strands, strand diameter, and distance. Peters and Manoli [6] proposed using multi-wire PCB coils, where each trace is replaced with many parallel wires connected at both endings for efficient telemetric energy transfer. Recently, Laskovski *et al.* [7] proposed a 4-layer stacked PCB coil, whereas Givrad *et al.* proposed a 2-layer PCB coil for biomedical implants.

These pionering studies provide an excellent theoretical framework for modeling aggregated coil structures, as well as rich experimental data. In this paper, we aim to leverage this data by evaluating the multi-layer coils performance in terms of their heating effects on the skin.

III. Multi-Layer Coils

In this section, we describe and characterize coils with different number of layers, *i.e., multi-layer coils*.

A multi-layer coil can be manufactured by stacking multiple layers of single layer coils (one such single-layer coil used in this paper is given in Fig. 1a), and connecting these stacked coils in series.

To find out the self inductance of a multi-layer coil, we need to first determine the self-inductance (L) of a single layer coil. Since, each layer of our multi-layer coil is a single-layer spiral coil and has a circular-shape, its L can be simplified from Eq. (2) in [8] as,

$$L = \frac{\mu_0 \cdot N^2 \cdot r_{avg}}{2} \left(\ln(2.46/\varphi) + 0.2\varphi^2\right) \tag{1}$$

where N is the number of turns in the coil, and φ, and r_{avg} can be given as,

$$\varphi = \frac{r_{out} - r_{in}}{r_{out} + r_{in}}, \qquad r_{avg} = \frac{r_{out} + r_{in}}{2} \tag{2}$$

The self inductance of a multi-layer coil is contributed by the self inductance of each layer, and the mutual inductance in between each coil pair. Thus, the self-inductance of a multi-layer coil can be given as,

$$L_{ML} = \sum_{i=1}^{S} \left(L_i + \sum_{\substack{1 \le j \le S \\ j \ne i}} M_{ij} \right) \tag{3}$$

where S shows the total number of layers in the multi-layer coil, and L_i shows the self-inductance of the coil at layer i, which can be calculated using Eq. (1). Since, for the multi-layer coil, all layers are identical, the self inductance of each layer is the same ($L_i = l$, $i = 1 \ldots S$). Then, Eq. (3) can be simplified as

$$L_{ML} = l \cdot S + \sum_{i=1}^{S} \left(\sum_{\substack{1 \le j \le S \\ j \ne i}} M_{ij} \right) \tag{4}$$

The expression for the mutual inductance between two coils derived in [9] is used here to calculate M_{ij} between layers i and j and the results are tabulated in Table I based on the distance between layers i and j. The mutual inductances between two layers of the multi-layer coil can be defined with the identical expression, and they only differ at the distance.

To characterize multi-layer coils, first, six identical, single-layer, planar, spiral coils are made using thin Litz wire (AWG # 42 with 8 strands). The Litz wire provides an extremely thin layer, thus allows the stacking without increasing the coil thickness too much. Each of these coils have a diameter of 2 cm, and 30 turns. By stacking these single-layer coils together, multi-layer coils up to 6 layers are made and characterized at 1 MHz using an HP4194A Impedance Analyzer. For each number of layers except the 6-layer case, 5 coils are made using randomly selected combinations of the single coils. Only one 6-layer coil is made giving a total of 26 coils. In Figs. 2-4, various measured parameters of these coils are shown. Individual coil measurements are shown as single data points. The curves are then generated by using the average value of the 5 coils made for a particular number of layers. One of the 5 coils for each number of layers is then used to facilitate the experiments given in Section IV.

Fig. 2 shows the change in self-inductance and the quality factor of the coils with the number of layers. In Table I, mutual inductances between pair of layers in the multi-layer coil is calculated following [9], and given based on the distance between layers. The calculations (dashed line) matches with the measured data closely, and the self inductance increases as the number of layers increase as expected. The increase is super-linear since each layer added contributes to the total self inductance in two aspects (1) the self inductance of the added layer, and (2) the mutual inductance between this layer and all the other layers. The first factor contributes a constant increase with each added layer, whereas the second factor increase with every added layer. The quality factor also increases with number of layers up to and including 4-layer case as expected following the increase in L, however this increase is not sustained for higher number of layers. The saturation and decline in Q is due to the faster increase in the ac resistance with respect to the increase in L as shown in Fig. 3. This is also reflected in the measurements of SRF (self-resonant frequency) and f_{peak} (the frequency value where the coil Q is the highest) as shown in Fig. 4.

TABLE I: Mutual inductance between different coil layers. Each coil layer adds a 0.3 mm to the thickness, the tape in between layers also adds 0.015 mm to the thickness.

Between layers	**Distance [mm]**	**Mutual Inductance [μH]**
i and $i \pm 1$	0.015	10.98
i and $i \pm 2$	0.330	10.17
i and $i \pm 3$	0.645	9.43
i and $i \pm 4$	0.960	8.75
i and $i \pm 5$	1.275	8.12

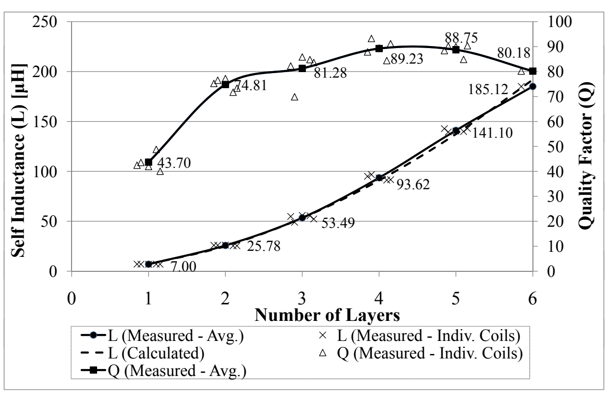

Fig. 2: The change of the self inductance (L) (y-axis on the left) and the quality factor (Q) (y-axis on the right) with respect to the number of layers. The L from Eq. (4) is also given and in good agreement with the measured data.

IV. Experiment Setup and Performance Results

In this section, a TETS with secondary coils using different number of layers characterized in Section III is evaluated

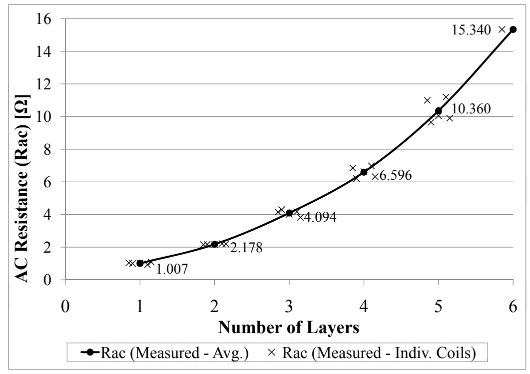

Fig. 3: The change of the *ac* resistance (R_{AC}) with respect to the number of layers.

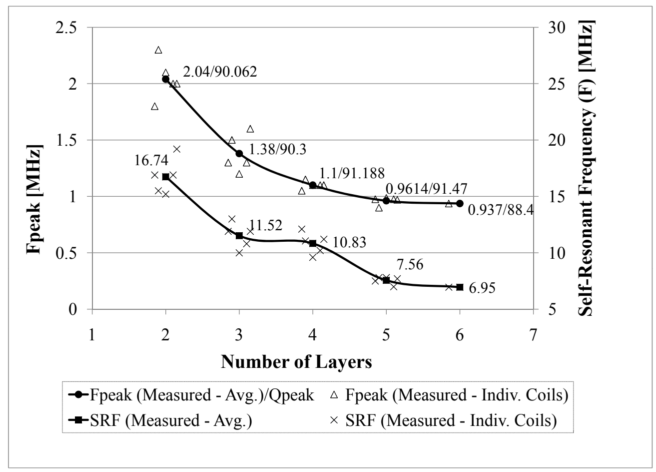

Fig. 4: The change in f_{peak} (y-axis on the left) and SRF (y-axis on the right) with respect to the number of layers.

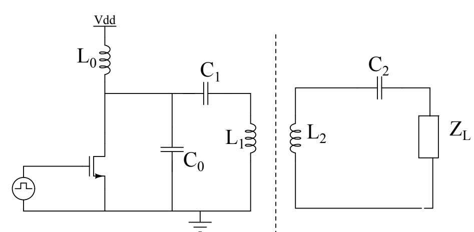

Fig. 5: TETS circuit diagram.

to determine how long such a system can deliver a pre-determined power to a load without exceeding the allowed temperature (*e.g.,* 1 or 2^oC) increase. The circuit diagram for the test setup is shown in Fig. 5. The primary circuit is a Class-E amplifier, where both the resonant frequency of the primary tank circuit (L_1, C_1) and the input oscillator output frequency are set as 1 MHz. The air core primary coil, which is wound with Litz wire of size AWG # 35, has a self inductance of 19 μH, and a Q of 67. The diameter of the primary coil is 25.4 mm. For the secondary coil, planar spiral coils with one to six layers and wound with Litz wire of size AWG # 42 with 8 strands are evaluated. For each

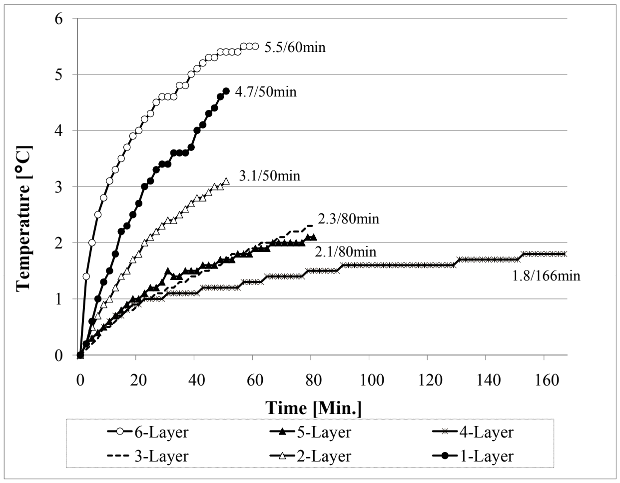

Fig. 6: Skin temperature rise with time, when constant power is applied to the primary.

secondary coil, the C_2 capacitance value is selected such that the resonant frequency of the secondary tank circuit (L_2, C_2) stays the same as the primary tank circuit resonant frequency (at 1 MHz). The load is fixed at 20 Ω.

For the experiments, a 1 cm thick slab of porcine meat (consisting of skin, fat and muscle tissues) is used to evaluate the heating effects of the TETS on the biological tissue. Prior to use, the meat slab is kept at room temperature for about 1 hour. Once the meat temperature reaches to a stable temperature (*i.e.,* less than 0.1^oC change in the temperature for at least 10 minutes, it is placed in between the primary and the secondary coils. The primary coil is placed inside a plastic enclosure to mitigate the skin temperature increase by eliminating direct contact between the primary coil and the skin [10], but also increasing the distance between the primary and the secondary coils about an additional 1 mm.

Once the circuit is setup the input power from the DC power supply is applied to the system. For each secondary coil the input power is set such that the power delivered to the load is fixed at 80 mW. The experiments are carried in a styrofoam box for thermal isolation from the environment. The meat temperature is measured every 2 minutes using a Keithley 871 Digital Thermometer (Keithley Instruments, Inc., Cleveland, OH). The power is briefly turned off (about 2 seconds) during the measurements to avoid the magnetic field to interfere with the measurements.

Skin temperature increase with time for different number of layers when the primary and secondary coils are aligned as shown in Fig. 6. When the secondary coil has only one layer, the skin temperature increase is rather rapid, and reaches to 1^oC in 6 minutes, and to 2^oC in about 13 minutes, and the temperature increases almost 5^oC within 50 minutes. On the other hand, adding more layers to the coil certainly reduces the heating effect on the skin up to and including 4 layers. Even for the 2-layer coil, the time to reach a certain temperature is increased over 60% compared to a single layer coil (10 and 22 minutes for 1 and 2^oC increases, respectively). For the 4-layer coil, the increase in time is quite significant, where it takes more than 22 minutes to reach to a 1^oC increase (3.6 times more compared to a single layer coil). Furthermore, the temperature increase slows down such that even after 166 minutes, the temperature increase is still at 1.8^oC and stable. This means an increase in duration over 16 times with respect to the single-layer coil to increase the skin temperature for 2^oC. However, this improvement does not continue for the 5- or 6-layer coils.

Further tests are performed for the case where the primary and the secondary coils are misaligned by a distance equal to the radius of the secondary coil (1 cm) (*i.e.,* the center of the primary coil is aligned to the outer rim of the secondary coil). To show a measurable time range for the single-layer coil in the misalignment case, the output power is reduced to 50 mW. The advantage of multi-layer coils is clear in the misalignment case as well, where using the 4-layer coil the time to have a 1^oC, and 2^oC increase is 3.6, and 5.3 times longer compared to the single-layer coil, respectively.

V. Conclusions

The low power transfer efficiency is a major problem for the TETS since it causes unwanted increase in skin temperature. In this paper, this problem is addressed using multi-layer secondary coils, which allow an increase in power transfer efficiency without increasing the coil diameter. Since, thin Litz wire is used, the thickness of the multi-layer coil is also kept small. Multi-layer secondary coils are shown to increase the duration of safe power delivery.

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