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Design of Double Layer Printed Spiral Coils for Wirelessly-Powered Biomedical Implants

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Abstract—**In this paper employing double layer printed spiral coils (PSCs) is proposed for wireless power transmission in implantable biomedical applications. Detailed modeling of this type of PSCs is presented. Both calculations and measurements of fabricated double layer PSCs indicate that this structure can decrease the size of typical single layer PSCs without any change in the most important parameters of the coils, such as quality factor. Also, it is shown that with equal PSC dimensions and design parameters, double layer PSCs achieve significantly higher inductances and quality factors. Ultimately, a pair of double layer PSCs with a distance of 5 mm in air is used in an inductive link. The power transfer efficiency of this link is about 79.8% with a carrier frequency of 5 MHz and coupling coefficient of 0.189.**

I. Introduction

INDUCTIVE powering is one of the most common ways of wireless power transmission to implantable biomedical microsystems. In this method, as illustrated in Fig. 1, the wireless link is composed of a pair of inductively-coupled coils, which are a few millimeters apart. Electric excitation of the external (primary) coil induces a voltage on the internal (secondary) coil, while both sides of the link are tuned to the same resonant frequency. This voltage is then rectified and regulated in order to be used as voltage supply for the implanted circuitry.

In implantable biomedical applications the carrier frequency of the power link is not typically chosen more than a few tens of megahertz [1]-[3]. This is mainly due to the fact that the power dissipation in the tissue increases with the carrier frequency. Additionally, based on electromagnetic safety standards such as [4], the amount of energy radiated by the primary coil has to be limited. As a result of these limitations, the power transfer efficiency of inductive links is of great importance. This efficiency, as discussed in [5], is dependent on the coupling coefficient (k) between the primary and secondary coils, and also to the quality factor of the coils. Therefore, for achieving high power transfer efficiency, these two parameters of the coils should be as high as possible. Another important issue in designing wireless links is the size of the implanted receiver, which should be kept as low as possible due to the limited space available inside the body.

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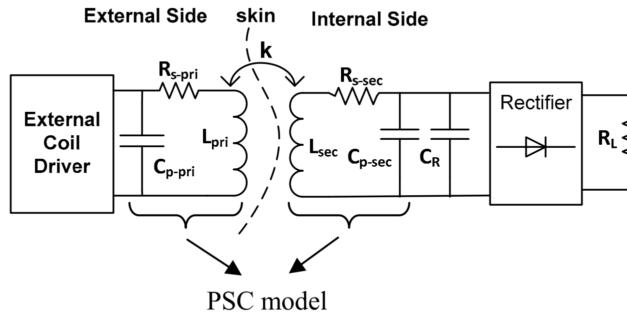

Fig. 1. Schematic of an inductive link for power transmission.

Recently, using PSCs in inductive links has drawn a lot of attention [1], [2], [6]. This type of coils, in comparison with wire-wound coils, benefits from a planar structure. Moreover, PSCs can be easily produced by standard microfabrication technologies.

In this paper design of double layer square-shaped PSCs for power telemetry is presented. By employing this technique, same quality factors and inductances of single layer PSCs can be achieved with smaller coil dimensions. In other words, with equal dimensions, double layer PSCs show significantly higher quality factors. Modeling of double layer PSCs is studied in section II. In section III important parameters of single and double layer PSCs are compared based on both calculations and measurements. Section IV covers the experimental results of inductive links, which take advantage of double layer PSCs. Finally, conclusions are provided in section V.

II. Theoretical Modeling of Double Layer PSCs

A. Inductance

The inductance of a single layer PSC can be approximated as [7]

$$L_{single} = \frac{1.27\mu_0 n^2 (d_o + d_i)}{4}\left[ln\left(\frac{2.07}{\varphi}\right) + 0.18\varphi + 0.13\varphi^2\right] \quad (1)$$

where μ_0 is the permeability of free space, n is the number of turns, d_o and d_i are the outer and inner diameters of the coil, respectively, and $\varphi=(d_o-d_i)/(d_o+d_i)$.

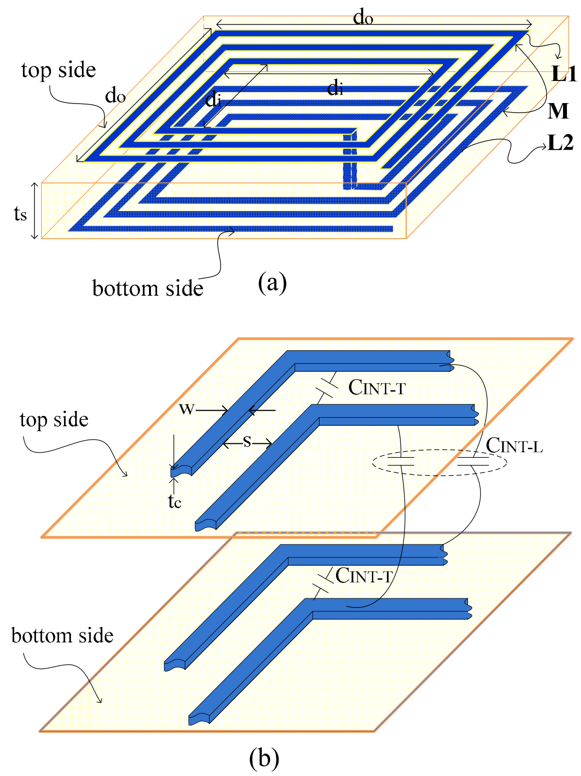

Fig. 2. (a) Schematic of a double layer PSC (b) Parasitic capacitances of this structure.

In double layer PSCs, as shown in Fig. 2(a), the equivalent inductance of the coil (L_{double}) can be calculated by considering two equal series inductances ($L1=L2=L_{single}$) with a coupling coefficient of k between them. Hence, L_{double} is expressed as

$$L_{double} = 2L_{single}(1+k). \tag{2}$$

Taking into account that $k=M/L_{single}$, for calculating k the mutual inductance (M) should be found first. From [8] for a pair of perfectly aligned parallel single-turn coils we have:

$$M_{ij} = \frac{2\mu_r \mu_0}{\alpha}\sqrt{r_i \cdot r_j}\left[\left(1-\frac{\alpha^2}{2}\right)K_{(\alpha)} - E_{(\alpha)}\right] \tag{3}$$

where μ_r is the relative permeability of the medium, $K_{(\alpha)}$ and $E_{(\alpha)}$ are the complete elliptic integrals of the first and second kind, respectively, r_i and r_j are the radii of two single-turn coils, and α is obtained from

$$\alpha = 2\sqrt{\frac{r_i \cdot r_j}{(r_i + r_j)^2 + d^2}} \tag{4}$$

where d is center to center distance between two coils. Finally, total mutual inductance of multi-turn coils is calculated by summing these partial values [8]

$$M = \sum_{i=1}^{n}\sum_{j=1}^{n} M_{ij}. \tag{5}$$

B. Capacitance

The parasitic capacitance of a single layer PSC (C_{INT-T}) can be found from [7]

$$C_{INT-T} \approx (\alpha\varepsilon_{rc} + \beta\varepsilon_{rs})\varepsilon_0 \frac{t_c}{s} l_g \tag{6}$$

where for a PSC on the FR4 substrate and without any coatings $(\alpha,\beta)=(0.9,0.1)$, $\varepsilon_{rc}=1$ and $\varepsilon_{rs}=4.4$ are the relative dielectric constants of air and substrate, respectively, t_c is the thickness of the conductor, and s is the spacing between the traces. l_g is the length of the gap between adjacent conductors, and is given by

$$l_g \approx 4n[d_o - (n+1)w - ns] \tag{7}$$

where w is the width of the conductor.

As it is shown in Fig. 2(b), in double layer PSCs another parasitic capacitor is formed between the conductors in top and bottom side of the PSC, with the substrate as a dielectric. This capacitance is expressed as [9]

$$C_{INT-L} \approx \frac{\varepsilon_{rs}\varepsilon_0 l_c w}{t_s} \tag{8}$$

where t_s is the thickness of the substrate and l_c is the length of the conductor in each layer, which is given by

$$l_c = 4nd_o - 4n^2 w - (2n-1)^2 s. \tag{9}$$

Thus, the total parasitic capacitance of a double layer PSC is obtained from

$$C_p \approx \frac{C_{INT-T}}{2} + C_{INT-L}. \tag{10}$$

This indicates that using double layer PSCs results in larger parasitic capacitances and reduces the self resonant frequency (SRF) of the coils. However, as shown in the experimental results of section III, the SRF is still far enough from the commonly-used power carrier frequencies.

C. Resistance

Similar to single layer PSCs, the DC resistance of double layer PSCs can be easily calculated by $R_{DC}=(\rho_c \times 2l_c)/(w \times t_c)$ where ρ_c is the resistivity of the conductor. Considering the skin effect at high frequencies, the AC resistance is approximated as [7], [10]

$$R_s = R_{DC} \frac{t_c}{\delta \cdot \left(1 - e^{-t_c/\delta}\right)} \quad (11)$$

where $\delta = \sqrt{\frac{\rho_c}{\pi \mu f}}$ is the skin depth, and μ is the permeability of the conductor.

D. Quality Factor

Based on the model of a coil shown in Fig. 1, the quality factor is defined as $Q=Im(Z)/Real(Z)$ [2] where Z is the equivalent impedance of the model. This results in

$$Q = \frac{\omega L - \omega\left(R_s^{\,2} + \omega^2 L^2\right)C_p}{R_s} \quad (12)$$

which can be approximated as $Q \approx \omega L/R_s$ for small C_p or low frequencies.

III. Comparison of Single and Double Layer PSCs

A single layer (PSC-S1) and a double layer (PSC-D1) PSC have been designed in such a way that their inductances and resistances are nearly the same. As shown in Table I, both PSCs have the equal track width and spacing. However, PSC-D1 is about 26% smaller than PSC-S1. On the other hand, as expected, measured SRF of PSC-D1 is lower than PSC-S1 due to larger parasitic capacitors. But, even this value of SRF is much higher than typical power carrier frequencies in biomedical implants, which are mostly below 13.56 MHz [7],[11],[12]. Additionally, quality factors of these coils are plotted in Fig.3 based on both calculations and measured values in a frequency range of 1-5 MHz. This figure shows that calculations are in good agreement with measurement results.

TABLE I
IMPORTANT PARAMETERS OF DESIGNED PSCS

	PSC-S1	PSC-D1	PSC-S2	PSC-D2	PSC-S3	PSC-D3
No. of Layer(s)	1	2	1	2	1	2
No. of Turns	1×12	2×8	1×17	2×17	1×8	2×8
d_o (mm)	15	11	20	20	11	11
d_i (mm)	2.9	2.9	2.9	2.9	2.9	2.9
w (mm)	0.2	0.2	0.25	0.25	0.25	0.25
s (mm)	0.3	0.3	0.25	0.25	0.25	0.25
R_{dc} (Ω)	0.85	0.95	1.24	2.8	0.35	0.77
L_{calc}^{*} (μH)	1.37	1.64	3.20	11.7	0.49	1.63
L_{meas}^{Δ} (μH)	1.40	1.57	3.23	10.9	0.53	1.56
Q_{calc}^{*}	6.2	7.1	10.3	18.3	5.7	8.8
Q_{meas}^{Δ}	7.3	7.9	11.9	18.5	6.7	10.2
SRF (MHz)	>110	92.2	71	21.5	>110	90.8

* Calculation results @ 1 MHz.
Δ Measurement results @ 1 MHz.

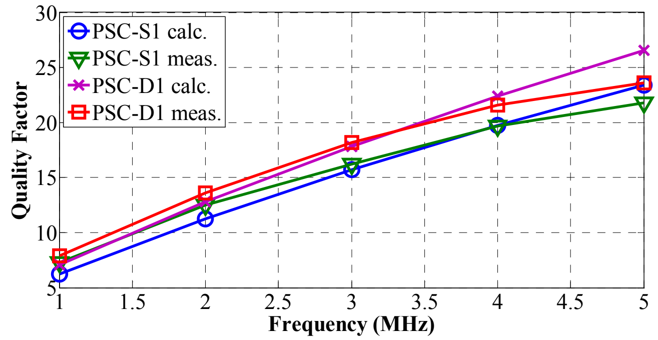

Fig. 3. Quality factors of PSC-S1 and PSC-D1 (calculation and measurement results).

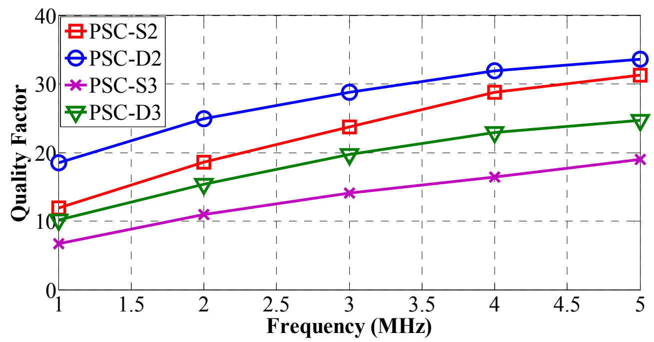

Fig. 4. Measured quality factors of two sets of PSCs.

From a different point of view it can be said that with equal coil geometries, double layer PSCs should have better properties in terms of inductance and quality factor. In order to validate this issue, two sets of single and double layer PSCs are designed as: set 1 (PSC-S2, PSC-D2) and set 2 (PSC-S3, PSC-D3). The outer diameter of coils in set 1 and set 2 are 11 mm and 20 mm, while all of the inner diameters and track widths/spacings are fixed at 2.9 mm and 0.25 mm, respectively. Complete design parameters along with calculation and measurement results are summarized in Table I.

Results show that, compared with single layer PSCs, the inductance of double layer ones has increased 237% and 194% in set 1 and set 2, respectively. Moreover, by using the double layer structure, the quality factor of single layer PSCs at 1 MHz has increased 55% in set 1, and 52% in set 2. This increase in quality factor is very important, as it plays a key role in power transfer efficiency of inductive links. Measured quality factors of these two sets of PSCs are plotted in Fig. 4 versus carrier frequencies of up to 5 MHz. In addition to the increase of quality factors with frequency, Fig. 4 again emphasizes on the notable difference between quality factors of single and double layer PSCs with similar design parameters.

It is worth mentioning that the SRF values obtained from the coils in set 1 are lower due to their larger outer diameters. Moreover, the lowest SRF, which belongs to PSC-D2, i.e., 21.5 MHz, is still high enough in comparison with the low carrier frequencies of power links in biomedical implants.

TABLE II
COUPLING COEFFICIENTS OF PSC PAIRS*

	Set	Primary	Secondary	k	$(k_2-k_1)/k_1$
Single Layer Transmitter	1	PSC-S2	PSC-S3	0.17	6.4%
	2		PSC-D3	0.181	
Double Layer Transmitter	1	PSC-D2	PSC-S3	0.175	8%
	2		PSC-D3	0.189	

* d=5 mm.

IV. POWER TRANSMISSION BY DOUBLE LAYER PSCS

At first, the effect of double layer architecture on coupling coefficient of PSC pairs is investigated. For this purpose, PSCs with smaller outer diameters (PSC-S3 & PSC-D3) are considered as receiver coils. Once power is transmitted by PSC-S2, and one more time its double layer counterpart (PSC-D2) is used as the transmitter. Results of these four experiments are summarized in Table II. It can be seen that when both sides of the link benefit from double layer PSCs (PSC-D2 & PSC-D3), coupling coefficient increases about 11%, compared with the state that only single layer PSCs (PSC-S2 & PSC-S3) are used.

For power transmission, an inductive link with PSC-D2 as the primary coil, and PSC-D3 as the secondary coil is used. The resistive load (R_L) and the distance between the PSCs are set to 270 Ω and 5 mm, respectively. Power transfer efficiency for a link with no rectifier is calculated by dividing the load power (P_{Load}) by the power delivered to the primary coil (P_{in}), and can be expressed as [7]

$$\eta = \frac{k^2 Q_1 Q_2}{1+k^2 Q_1 Q_2} \cdot \frac{Q_2}{Q_2 + Q_L} \tag{13}$$

where Q_1 and Q_2 are quality factors of primary and secondary coils, respectively, and based on the model shown in Fig. 1 $Q_L \approx \omega R_L(C_R+C_{P\text{-}Sec})$ [7]. Calculated and measured power transfer efficiencies are plotted in Fig. 5 for carrier frequencies of 1 MHz to 5 MHz. The coupling coefficient between the PSCs is about 0.189, and the maximum efficiency of 79.8% is achieved at 5 MHz. Finally, important parameters of the link are presented in Table III for two different loading conditions.

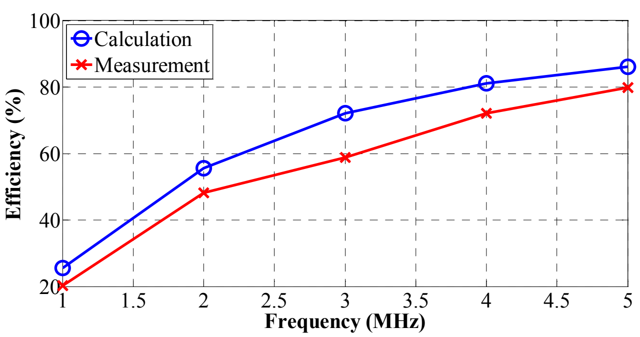

Fig. 5. Power transfer efficiency of the link, when PSC-D2 is the primary coil, and PSC-D3 is the secondary coil with a distance of d=5 mm and R_L=270 Ω.

TABLE III
POWER TRANSFER EFFICIENCY FOR DIFFERENT R_L*

	P_{in} (mW)	P_{Load} (mW)	η (%)	k
R_L=270 Ω	3.7	2.94	79.8	0.189
R_L=560 Ω	4.8	3.09	63.7	0.189

* Power transfer efficiency of the link with a carrier frequency of 5 MHz, when PSC-D2 is the primary coil, and PSC-D3 is the secondary coil with a distance of d=5 mm.

V. CONCLUSION

Design of double layer PSCs for the wireless link of implantable biomedical microsystems was studied. Detailed models of these PSCs and experimental results show that this technique is capable of increasing the coupling coefficient of the PSC pairs, the quality factor of the coils, and consequently the power transfer efficiency of inductive links without changing the area used by the PSC. On the other hand, due to the fact that double layer PSCs have higher parasitic capacitances, frequency of the carrier should be chosen by considering the SRF values of the coils.

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