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Modeling, fabrication and characterization of micro-coils as magnetic inductors for wireless power transfer

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ABSTRACT

This work presents modeling, fabrication and characterization of planar microcoils for wireless power transfer in medical implanted devices, proposing integrated technology as a way to reduce the dimensions and achieve higher efficiency. The wireless power transfer (WPT) architecture is composed by: a primary coil carrying the alternating current signal to generate a magnetic field and the receiving coil to convert magnetic field in current, that is located parallel to the primary one with a gap between the two inductors.

In the proposed design the two microcoils are circular with short-circuited turns to minimize electrical resistance. The electrical measurements on the fabricated test structures with different pitch sizes show a dramatic reduction of coil resistance to few ohms with respect to classic coil design. The experimental values of the resistance and inductance (from 24 to 45 nH) are in good agreement with the analytical model.

The efficiency of fabricated microcoils for wireless power transfer is predicted by Finite element method (FEM) at 10 kHz modeling in terms of coupling factor ranging the distance of the inductors from 0 to 1 mm. FEM results show that the transfer efficiency can be further enhanced by the introduction of a ferromagnetic material on the back side of each coil in order to confine the magnetic field. High coupling factor above 65% can be achieved with this shielding layer, even with lowest pitch value and high coil distances.

1. Introduction

In last years, market and technology are addressing a growing interest in energy generation, transfer and storage. One of the most attractive topics concerns the wireless power management in applications such as medical implants, battery charger for portable devices or radio-frequency identification (RFID) tags. For biomedical implantable devices, the replacement of the device battery requires periodic surgeries and it forces the patients to pain and long convalescence period. To avoid surgeries and/or transcutaneous wiring, which cannot be placed for long periods of time, the medical devices can be recharged by a wireless power transfer, which relies on drawing two coils up, the primary is handled by user and the secondary is in the assisting device [1–4]. Therefore the power is transferred through the skin and at least the secondary coil must be as small as possible. The wireless power transfer exploits inductive magnetic coupling: the transmitter (or primary) coil is the active part of the system and it transfers power to the receiving (or secondary) passive coil. The power-transfer efficiency strongly depends on electrical parameters (as self and mutual inductances), coupling between the two coils and geometrical specifications, e.g. size of the coils, distance between them, relative location, properties of the separating and surrounding medium. For these reasons, geometrical modeling of microcoils represents a fundamental step to optimize the whole system. The working frequency for wireless technology can be kept low [5], making this technique suitable for safe medical applications. Small sizes and high efficiency are the main requirements to be considered for the design of these systems. As the distance between the two coils increases, the energy transferred in the secondary coil drastically decreases. In order to achieve significant power transfer efficiency, the optimization of the coils design is fundamental.

In this paper, modeling, fabrication and electrical characterization of low resistance planar microcoils are discussed. Compared to classical inductors design, an alternative short-circuited turns configuration has been chosen to reduce series resistance and power consumption. The fabrication steps

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and the setup for electrical measurements of self-inductances are described, as well as the electronic scheme for wireless power transfer application. Electrical parameters are evaluated by analytical models and compared with experimental. Finally the magnetic inductive coupling between the two coils is studied in air by COMSOL simulations, in order to maximize the power transfer efficiency optimizing design parameters as distance between the inductors.

2. Design and fabrication of low resistance planar microcoils

To design a micro wireless power transfer system with high efficiency, the microcoils are required to show high self inductance and low series resistance. As previously discussed, small size is desirable for the application of these microcoils to medical implanted devices. However the miniaturization of the inductors will cause a reduction of the self inductance. A trade-off between limited occupied area and performances can be found optimizing the number of turns and at the same time decreasing the microcoil resistance.

Electrical resistance and self inductance of the microcoils can be evaluated by analytical model and compared with the experimental values. The frequency-independent component of the electrical resistance is calculated by the Ohm's law:

$$R = \rho l/A, \tag{1}$$

being ρ the electrical resistivity of aluminum, l the total length of the wire and A its cross-section dimension. The frequency-dependent part is caused by the skin effect: alternating currents through the coil wire cause an eddy electrical field inside the conductor. The total effect is the shifting of the current toward the surface of the metal track in a thickness called "penetration depth", increasing the effective resistance of the wire. This effect becomes significant at higher frequency and when the penetration depth δ, expressed by

$$\delta(\omega) = (2\rho/\mu\omega)^{1/2}, \tag{2}$$

is smaller compared to the diameter of the conductor. Typically, at 1 MHz the penetration depth in aluminum wires is $\delta \approx 80\ \mu\text{m}$, larger than the wire dimensions of presented microcoils, and therefore can be neglected.

For the evaluation of the self-inductance, a first calculus can be performed by starting from the self-inductance of a single turn. For a square-shaped loop of side D, the self-inductance can be evaluated from geometrical quantities, as reported in the following formula [6]:

$$L_{s,square} = \frac{2\mu D}{\pi}\left[\ln\frac{4D}{b+h} + 0.894\frac{b+h}{4D} - 0.66\right], \tag{3}$$

considering the shape of the wire rectangular and being b and h respectively the width and the thickness of the metal wire. The geometrical parameters are expressed in meters (m), the self-inductance in henry (H).

To obtain larger values of self-inductance, the number of loops can be increased. In this case, the following formula is used for multi-turns coil having a square shape [6]:

$$L_s = \frac{\mu D^3}{4\pi p^2}(1-\alpha^2)(1-\alpha)\left[\ln\frac{1+\alpha}{1-\alpha} + 0.2235\frac{1-\alpha}{1+\alpha} + 0.726\right] \tag{4}$$

where D is the side of the outer square of the coil, p the pitch between adjacent turns, α the fill ratio expressed as $\alpha = D/d$ (d side of the inner square of the coil) In Fig. 1, a schematic view of a circular coil and its geometrical parameters is illustrated.

The inductance of the microcoil strongly depends on the spatial density of the turns, expressed by the pitch and the fill ratio α. If the outer diameter of the coil is much bigger than the wire width ($D \gg b$), the ratio between the self-inductance of a circular and a square shaped coil is approximately given by

$$L_{circ}/L_{sq} = \pi/4, \tag{5}$$

that is the ratio of their areas [6]. This approximation has been used to calculate the self-inductance of the fabricated microcoils and to compare it with the experimental values. The geometrical parameters of the coils, the series resistance and the calculated self-inductance are summarized in Table 1

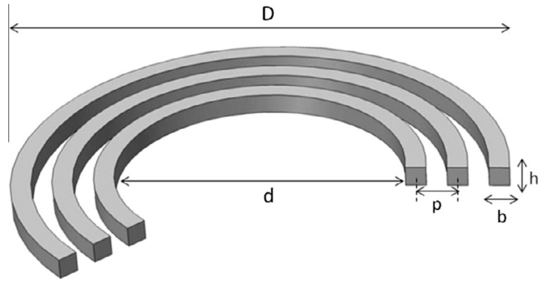

Fig. 1. Schematic cross section of a circular-shape microcoil: d and D are, respectively the inner and outer diameter, p the pitch between adjacent turns, h and b the thickness and the width of the metal wire.

Once having designed and modeled the electrical specifications of the planar microcoils, an appropriate electronic system must be developed to couple a primary coil (transmitter) to the secondary coil (receiver). From the structural point of view, a wireless power transfer electronic system is composed by the following parts: a coil driver (e.g. voltage controlled half bridge); the primary coil (or an array of primary coils) to generate the magnetic field; the receiving coil (or an array of receiving coils) in proximity to primary which converts field into current; a receiving resonant circuit; a full bridge rectifier circuit [7–9]. Depending on the system architecture, the wireless power consortium (WPC) defines different types of WPT systems and their specifications as voltage input and operational frequency range [10]. We will consider the power transmitter design of A type, which includes only a single primary coil and a single secondary coil, as in our case of study. The model of the electronic system is shown in Fig. 2: the wireless power transfer efficiency can be calculated by measuring the voltage V and the current A to the load (R_L). In Fig. 2, three main blocks can be identified relative to the primary coil (L_p), the secondary coil (L_s) and the full bridge diode rectifier. The first two areas are briefly explored next and shown in Fig. 3.

The transmitter part of the system consists of the primary coil connected with a serial resonance capacitor (C_p) and driven by a square wave generator (V_{in}), where the resonant section amplifies the original voltage signal V_{in}. The resonance is given by.

$$f = 1/(2\pi(L_pC_p)^{1/2}). \tag{6}$$

The receiver coil part is composed by a second resonant circuit with two resonant capacitances: the first capacitance C_s enhances the power transfer efficiency, while L_d has the purpose of enabling a resonant detection method.

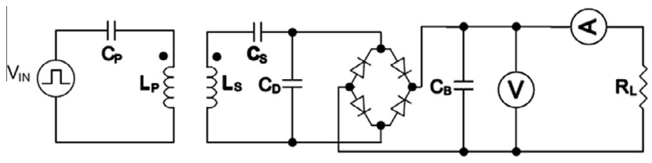

Fig. 2. Model of electronic system for wireless power transfer. From [8].