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Letter

A study on geometry effect of transmission coil for micro size magnetic induction coil

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ABSTRACT

The effects of transmission (Tx) coil structure have been studied for micro-size magnetic induction coil. The size of the receiving (Rx) coil should be shrunk to the micrometer level for the various new applications such as micro-robot and wireless body implanted devices. In case of the macro-scale magnetic induction coil, the power transmission efficiency is generally considered to be higher as the inductance of the transmission coil became larger; however, the large size difference between macro-size Tx coil and micro-size Rx coil can decrease the power transmission efficiency due to the difference of resonance frequency. Here, we study a correlation of the power transmission with the size and distance between the macro-size Tx and micro-size Rx coils using magnetic induction technique. The maximum power efficiency was 0.28/0.23/0.13/0.12% at the distance of 0.3/1/3/5 cm between Rx and Tx coil. In addition, more efficient wireless power transferring method is suggested with a floating coil for the body implantable devices. The voltage output increased up to 5.4 mV than the original one Tx coil system. The results demonstrated the foundational wireless power transferring system with enhanced power efficiency.

1. Introduction

Recently, various implantable, wearable and flexible devices have been studied intensively [1–6]. For such applications, wire connection is the mainstream to transfer power and data, so far. However, the wiring causes the inconvenience, and induces severe damages to the body implantable devices. Therefore, the batteries are commonly used as an alternative of the wiring of the devices. The batteries implanted in the human body are needed to be recharged occasionally. Therefore, the wireless power transfer can be the ideal solution for rechargeable batteries without surgery [6–8]. Magnetic induction coil is one of the best solutions for powering the devices wirelessly because the efficiency of the power transmission is quite high [9,10]. Even though the intensity of the magnetic wave strongly depends on a magnetic permeability, almost all mediums including the air, water, wood and metals have similar values, so that the power transmission via magnetic induction does not have unwanted path loss [11].

As the implantable devices get smaller, the magnetic induction coil should be shrunk to the micro level. The problem is that the micro coil power efficiency is lower than that of the macro scale coil due to the decrease of inductance and geometry effects. Generally, large size transmission (Tx) coils show high efficient power transfer in macro scale however, in micro-scale receiving (Rx) coil, Tx coil optimization is needed to have high power efficiency [12]. Depending on the size of Tx coil and the distance between the Tx and the Rx coils, the highest power efficient Tx coil varied due to the size effect and the resonance frequency of the Tx and the Rx coils. Therefore, enhancing power transfer efficiency for micro coil is desired depending on the external environment.

In this study, we experimentally demonstrated the dependence of the distance between the Rx and the Tx coil for high efficient wireless powering system with various Tx coil sizes and configuration. In particular, for the body implantable devices or micro-robots, enhanced wireless powering coil structure with floating coil is suggested.

2. Material and methods

2.1. Fabrication of micro coil (Rx) and transmission coil (Tx)

Fabrication process of micro coil is performed as following: (1) A glass was cleaned by chemical solutions and O_2 plasma to be used as a substrate; (2) The contact pad was formed by lift-off process. Chrome (Cr) and Gold (Au) layer of 50 nm and 150 nm, respectively, were deposited on the photoresist (PR) patterned glass substrate by RF magnetron sputtering system at an input

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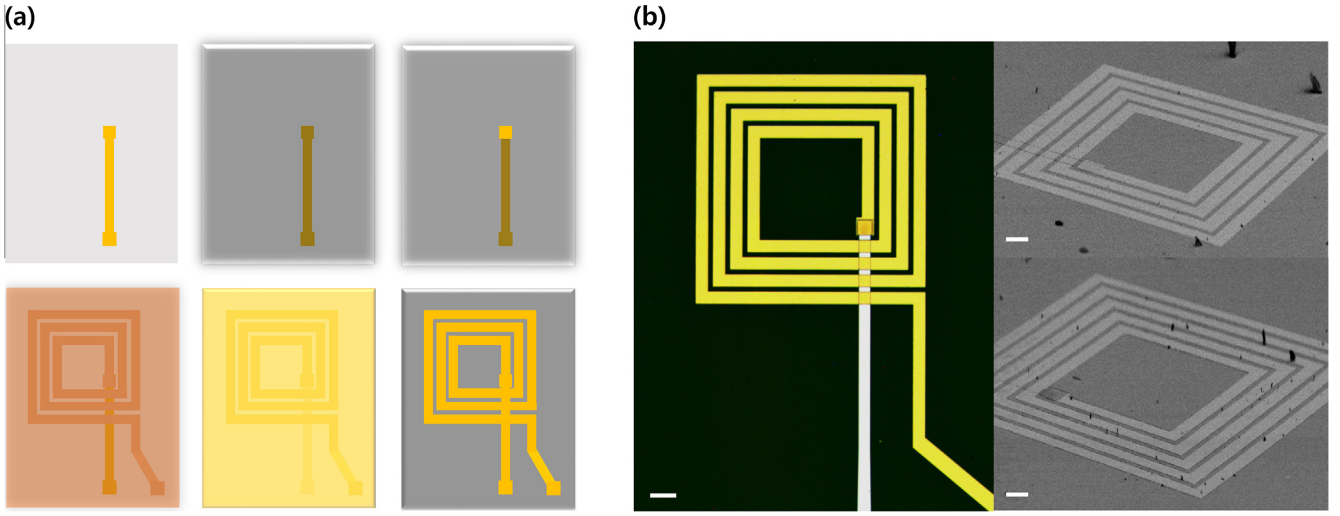

Fig. 1. Schematic diagram and images of wireless power transfer coils. (a) The fabrication process of the Rx micro coil. (b) The optical microscope image and SEM images of micro coils. The scale bar is 100 μm.

power of 200 W and a pressure of 5 mTorr; (3) The 200 nm of silicon oxide (SiO_2) is deposited by plasma enhanced chemical vapor deposition (PECVD) system as insulator between the contact pad and the micro coil; (4) The contact hole was etched by reactive ion etching with CF_3 and CHF_3 gas; (5) The micro coil was fabricated on the contact pad with Cr and Au layers and lift-off process. Fig. 1a shows the fabrication steps of a micro Rx coil. The solenoid type Tx coils with diameter of 10 cm, 5 cm and 1 cm were made for the comparison of wireless power transfer efficiency. The diameter of 1 mm copper wire was used as Tx coils and the height of all coils were 2 cm.

2.2. Experimental setup

Electro-magnetic characteristics of the Rx and the Tx coils were measured by network analyzer (Agilent technology E5061B). Input voltage, 10 V_{pp} and sine wave form in the range of MHz frequency, was induced through the function generator (Agilent technology 33250A) to Tx coils. The output voltage was measured by oscilloscope (Tektronix DPO3034) with different types of Tx coils and distances between the Rx and the Tx coils.

3. Results and discussion

The micro coils can be targeted to the body implanted devices, micro-robots or Internet of Things sensors. In this research, outer diameter of micro coils of 1000 μm and 800 μm with spacing widths of 40 μm and 20 μm were fabricated (Fig. 1b). The Tx coils are made with three different diameters 10 cm, 5 cm, and 1 cm, to study the effect of Tx coil position and structure for the wireless power transfer system.

The characteristics of the Rx and the Tx coils were analyzed in frequency domain as shown in Fig. 2. The inductance values of the 1000 μm and the 800 μm Rx coils are shown in Fig. 2a and the S_{11} parameters of Rx are shown in Fig. 2b. Due to the size effect and the number of turns in coil, 1000 μm design has a higher inductance than that of 800 μm coil structure as we expected. The resonance frequency was measured by S parameter value of network analyzer due to the measuring frequency limit of inductance meter (<30 MHz). The resonance frequency of 1000 μm and 800 μm coil is 2.1 GHz and the 2.5 GHz respectively. The values are quite higher than that of macro-size magnetic coil structures. Therefore, considering the resonance frequency of micro coil structure, inductive coupling principle is more appropriate for the wireless power transmission. Although resonance inductive coupling can have a better power transmission efficiency [13–15], the GHz range frequency is not an easy condition for various electrical components. The three different types of Tx coils are analyzed as shown in Fig. 2c and d. As the diameter of the coil decreases, the coil had smaller inductance value. The 10 cm coil shows a first resonance frequency at 17 MHz. From *S*-parameter analysis, other resonance frequencies are shown in 34 MHz, 53.5 MHz, and 69 MHz. For the 5 cm and 1 cm coils, the inductance increased with the increase of frequency (Fig. 2c). The smaller size coil shows the higher resonance frequency; 10 cm/5 cm/1 cm coil had the highest resonance frequency at 53.5 MHz/59 MHz/66.5 MHz, respectively. These characteristics of the Rx and the Tx coils, depending on driving frequency, determine the optimal condition in different environments such as the distance and the size effect between the Rx and the Tx coils.

To find mutual relation and optimal condition of power transmission between the Rx and the Tx coils, the characteristics of power transmission were analyzed according to the distance, the size of Tx coil, and the driving frequency which are main factors for inductive coupling power transmission (Fig. 3a). In here, the distance between two coils (Tx–Rx) were set to be 5 cm, 3 cm, 1 cm, and 0.3 cm which could be the real distance between the body-implanted device and the Tx coil in several external environments. The transmission power of 1000 μm/800 μm Rx micro coils was measured when 10 V_{pp} was applied to the 10 cm/5 cm/1 cm/0.3 cm Tx coils with different driving frequency up to 70 MHz.

As shown in Fig. 3b, the 10 cm Tx coil induces the higher power to the Rx coil than the 5 cm or 1 cm Tx coil at the distance of 5 cm between the Tx and the Rx coils. Considering the circular distribution of magnetic field from magnetic source, if the Rx coil is further apart than the diameter of the Tx coil, the loss of magnetic flux is quite high. An appropriate working distance for the 10 cm Tx coil without severe loss can be under the 10 cm. Therefore, the 5 cm and the 1 cm Tx coil designs are not suitable for the distance of 5 cm. Generally, the 1000 μm micro coil had higher power efficiency than that of the 800 μm micro coil. The peak voltage output is observed near 53.5 MHz which corresponds well to the resonance frequency of the 10 cm Tx coil (Fig. 3c). The wireless transmission voltage $V(t)$ can be expressed by