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Design of Two-Dimensional Lateral Antenna for Wireless Power Transmission to In Vivo Robotic Capsule

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Abstract

This paper presents two dimensional receiving coils to provide hundreds of milli-watt power via inductive link to in vivo robotic capsules, whose orientation are practically undetermined. The wireless power transmission system consists of a transmitter powered by class E power amplifier, and a receiver with three dimensional antenna, rectifier, and voltage regulator. As the 2D lateral antenna construction is more critical for the receiving antenna, two types of 2D antennas are introduced and evaluated by theoretic and experimental analyses. Experimental results verifies that the cross-type construction show better directional performance for receiving power than the cylindrical one for the 2D antenna. The former could deliver the power homogeneously regardless of its orientation, with less than 20 % of variation from the possible maximum power.

Key words : wireless power transmission, in vivo robotic capsule, inductive link, two-dimensional lateral antenna

Ⅰ. INTRODUCTION

In recent years the interest in wireless capsule-type endoscopes increased significantly, with efforts from various research institutes and companies[1-6]. The endoscopic capsule called M2A recently has been developed and commercialized by Given Imaging Inc.[4]. This is equipped with a CCD camera, an RF transmission, illuminating LED, and battery. While it moves by the peristalsis, a new version of wireless capsule endoscope, called 'in vivo robotic capsule', is being developed to provide thorough diagnosis of the concerned regions[6]. As the in vivo robotic capsule consumes considerable power compared to the passive capsule, batteries are not sufficient, requiring another means of power supply.

In this paper, we introduce a wireless power transmission system for the in vivo robotic capsule. As the robot capsule requires several hundreds of milli-watts power under the strict size limitation, we attempt to design a more efficient wireless power transmission system with small size for the in vivo robotic capsule. Radio frequency inductive link for energy transmission is selected considering various aspects such as its energy dissipation characteristic through the body and the availability of the electronic components. Because the robotic capsule moves along the intestines, the system must take into account not only the relative distance but also the orientation between the power transmitter coil and the receiver. While most wireless energy transmission systems consider only the distance, our system should take into account the orientation also[6-7].

Most capsules have a cylindrical shape with diameter of approximately 10 mm. By winding coils on their side walls, the longitudinal antenna coil can have the relatively sufficient cross-section and turns[3]. However, various configurations of antennas must be investigated for the lateral 2D antennas, due to the limited physical space. The lateral antenna should be fitted within the space comparable to two commercial silver-oxide batteries.

We present two possible 2-dimensional constructions for the lateral antennas. Their power characteristics against the orientation are analyzed, implemented and experimented in terms of the homogeneity of the received power against its orientation.

Ⅱ. TWO-DIMENSIONAL CONSTRUCTION OF THE LATERAL ANTENNA

For the lateral 2D antenna, we consider only combining two

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orthogonal coils due to the space limitation. Note that the construction with more coils requires the space not only for the coils but also the related electronics such as the matching capacitors and rectifying circuit elements.

Let us consider two receiving coils perpendicular to each other as shown in Fig. 1. The B is the magnetic field from the transmitting coil to receiving coil. The L_x and L_y are the receiving coil loops, and they are perpendicular to each other. When the magnetic field B is parallel to the x-axis and θ is the angle between the x- axis and the loop Lx as shown in Fig. 1, we can get the induced voltage V_x and V_y in the loops L_x and L_y as follows:

$$\psi_x = BS\cos\theta\cos\omega t, \quad \psi_y = BS\sin\theta\cos\omega t \tag{1}$$

$$V_x = -N\frac{d\psi_x}{dt}, \qquad V_y = -N\frac{d\psi_y}{dt} \tag{2}$$

Where S is the surface area of the coils and ω is the radial frequency of the magnetic field B.

The induced voltage has the same phase with varying amplitude according to the angle, and its direction is shown with arrows in Fig. 1. Therefore, if the two coils are connected in series the amplitude of the induced voltage is as follows:

$$V_{eff} = NBS\omega\sin\omega t\sqrt{2}\sin\left(\theta + \frac{\pi}{4}\right) \tag{3}$$

By simply connecting the two receiving coils, it is obvious from (3), that there exist angles where the induced voltage vanishes to zero. However, if we connect them in parallel after rectifying each of them, the induced voltage becomes the maximum of them of each loop, and it ranges from approximately 70 % to 100 % of the possible maximum as to the following equation:

$$V_{eff} = NBS\omega\sin\omega t\,\max(|\cos\theta|, |\sin\theta|) \tag{4}$$

A matching capacitor is usually added to retrieve the maximum power from an antenna. When the resonance properties of both antennas are the same and the pure resistance of each coil has the same value of R_c, then the available power can be expressed as follows[10]:

$$P_m = \frac{|V_{eff}|^2}{R_c} \tag{5}$$

The series connection after rectification yields the induced voltage with the same period and shape as V_{eff}, but with the magnitude of $\sqrt{2}$ times greater than that. However, the available power from the series connection is the same because the resultant internal resistance is doubled. Therefore, we will discuss only with parallel connection.

In this paper, we assume that the given space is the cylindrical space of 8 mm and 5 mm in the diameter and the height, respectively. It is to accommodate the comparable space to that of the 2 silver-oxide batteries. As the use of the ferrite core is inevitable for the limited spatial requirement, we can consider two possible constructions. One is inserting the ferrites cores inside the cylindrical space and winding coils on the surface (Fig. 2). The other is to wind the coils directly on the ferrites (Fig. 3).With the first construction the coil can have large cross section for the magnetic flux, while the entire length of the coils can be reduced for the given number of turns with the second one. Note from the equation (5) that the short coil length is advantageous to retrieve the power when the turn-flux is the same. We can expect that the second construction is better if the relative permeability is very high.

Ⅲ. EXPERIMENTS AND RESULTS

To construct the cylinder-type 2-dimensional antenna, we took eighty turns with Litz wire (38 AWG, NELA4/44SP, New England Wire Technologies, Lisbon, NH) along the height of a cylindrical frame (Acetal Plastic) with 8 mm in

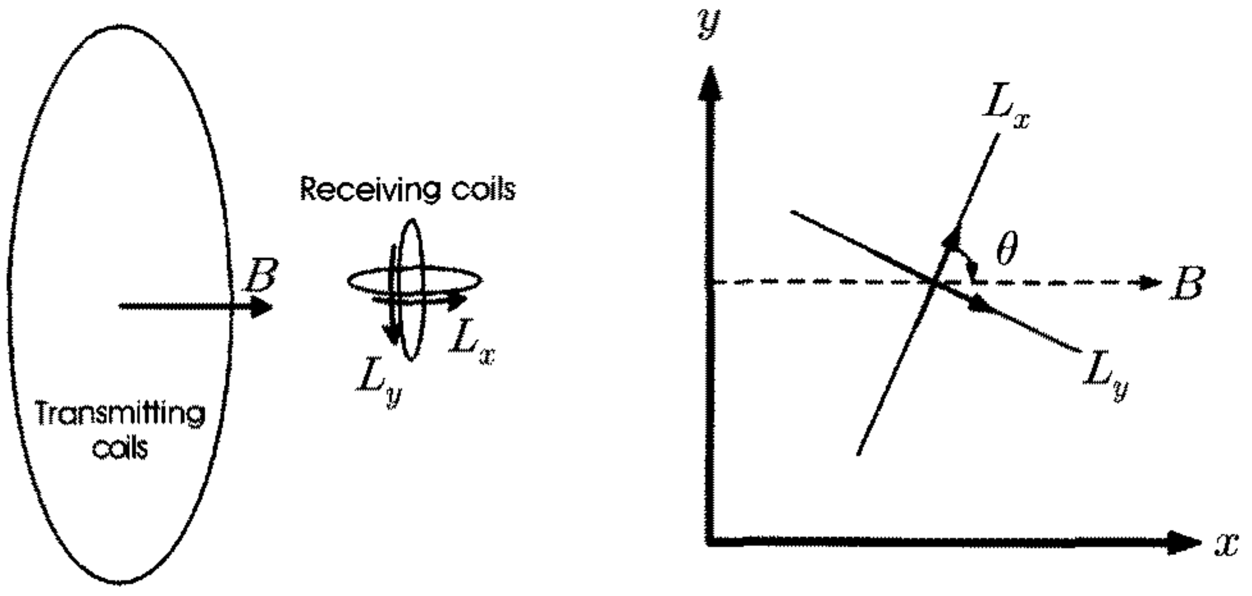

Fig. 1. The orientation of 2D receiving coils relative to the transmitting coil.

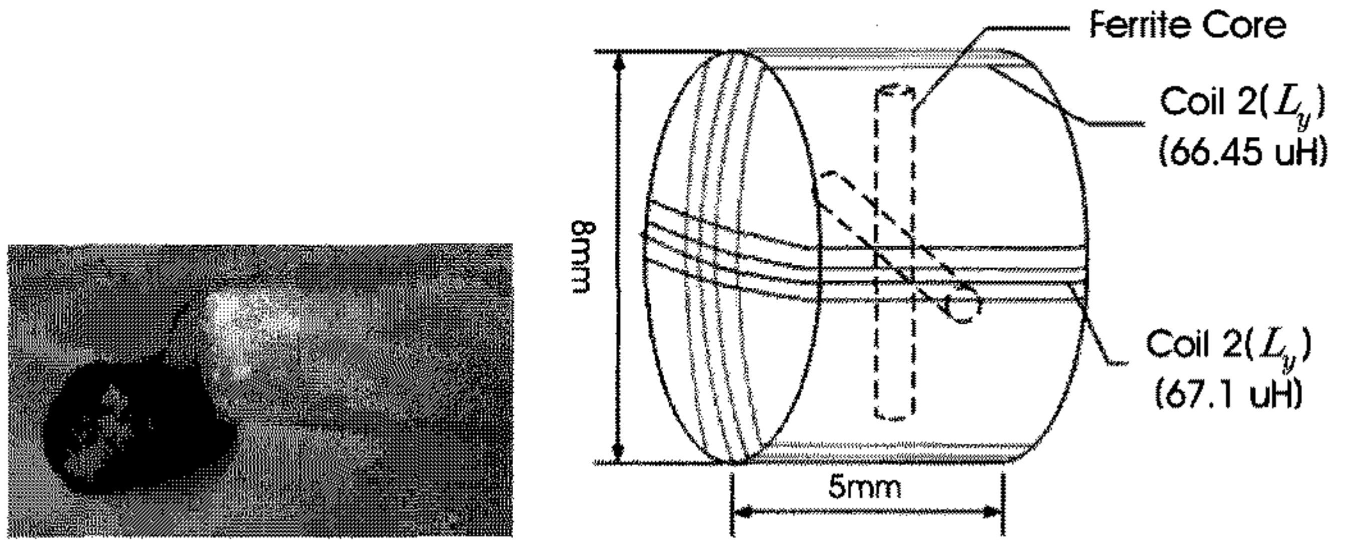

Fig. 2. Photo and structure diagram of the cylinder-type 2D antenna.

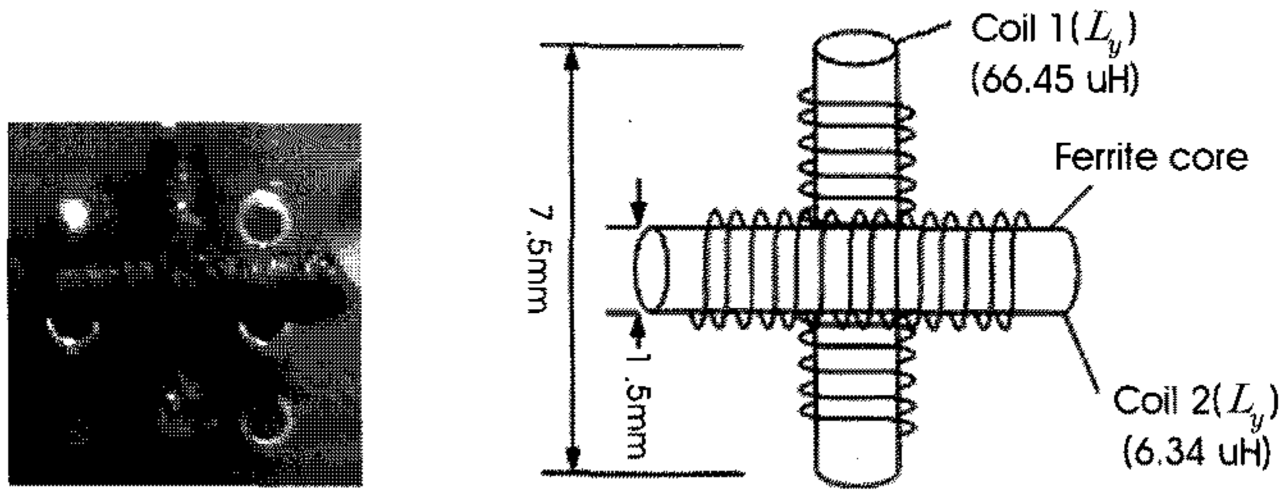

Fig. 3. Photo and structure diagram of cross type 2-dimensional antenna.

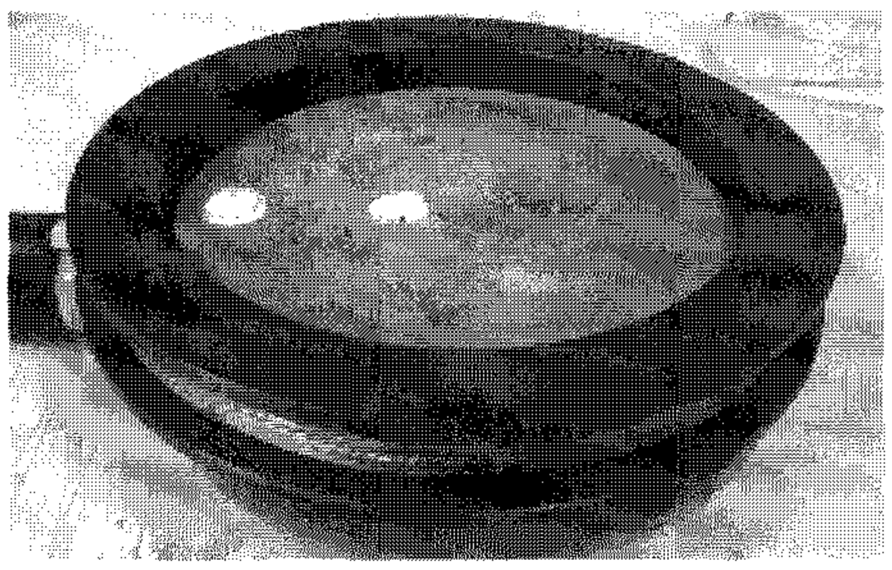

Fig. 4. The transmitting antenna.

diameter and 5 mm in length. We put ferrite cores (#3078990841, Fair-Rite Products Corp., Wallkil, NY) with 1.5 mm in diameter and 7.8 mm in length inside the receiver. The inductance of coil 1 (L_x) was 66.45 H, and that of coil 2 (L_y) was 67.1 H (Fig. 2).

For the cross-type antenna, the same ferrite cores with 1.5 mm in diameter and 7.8 mm in length were used, as shown in Fig. 3. We took thirty turns with the same twofold Litz wires (38 AWG) along the ferrite core, and then crossed two cores. The inductance of coil 1 (L_x) was 6.44 μH, and that of coil 2 (L_y) was 6.74 H (Fig. 3). In both constructions, the numbers of turns were maximized by experiments under the given spaced.

To evaluate the performance of the presented antennas, the transmitter coil was constructed with a cylindrical frame of 100 mm in diameter and 36 mm in height, and 26 turns of Litz wire (26 AWG, NELB66/44SPSN), as shown in Fig. 4. The class E power oscillator in the transmitter was operated at the frequency of 123 kHz. The magnetic field B generated by the transmitter was 4.55 Gauss at the test point that was the center of the transmitter coil.

The 2D antennas were positioned over the plastic plate on the top at the center of the transmission coil circle as shown in Fig. 5. To estimate the maximum available power, we constructed the circuit shown in Fig. 6. From measuring the maximum voltage across the variant load resistance R, the maximum power was taken from the following equation:

$$P_d = \max_{R}\left(V_s^2 / R\right) \tag{6}$$

where V_{rms} is the root mean square value of the voltage across the load resistance of R.

Fig. 7 shows the retrievable power according to the angle between the transmitting coil and the 2-dimensional antennas. The solid line depicts the power variation available from the cylinder-type antenna and the dashed line is for that from the cross-type antenna. The result shows that the deliverable power with the 2-dimensional antennas never diminished to zero as expected. It also shows that the power is available more homogeneously with the cross-type antenna than with the cylinder-type.

In order to get clearer insight, the deliverable powers were normalized with the maximum of each type of antennas. The results were shown in Fig. 8. The available power variation with the coil 1 of the cylinder-type antenna was also presented in the figure (the solid line) for reference. The figure shows that the power variation with the cross-type is less than 20 % of its maximum. It is noticeable that the minimum is not at the angle of 45 expected from (6). This was from the shift and

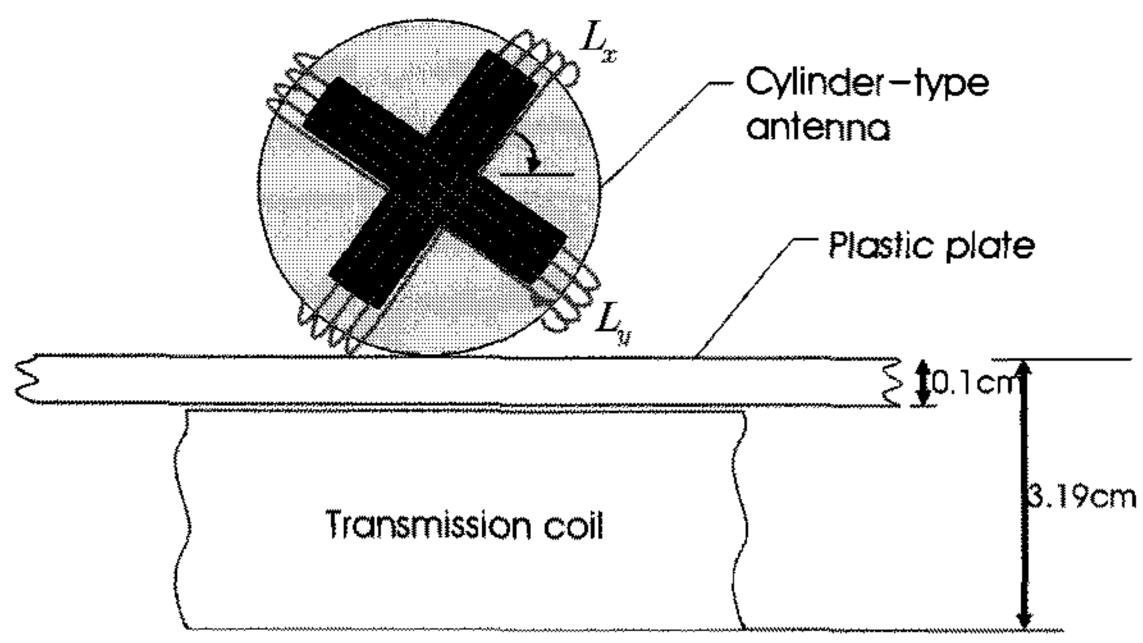

Fig. 5. Experimental set-up for the test of the cylinder-type antenna. The same set-up was applied to the cross-type antenna.

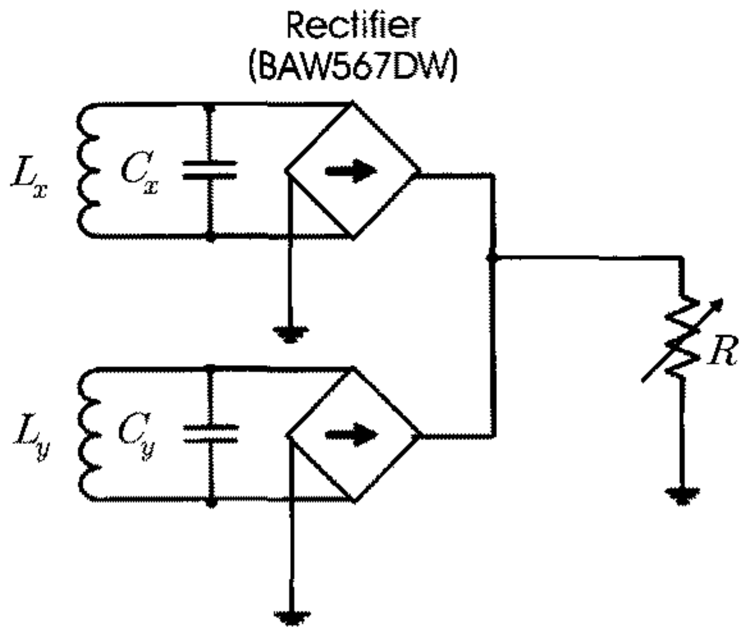

Fig. 6. Power measurement circuit.

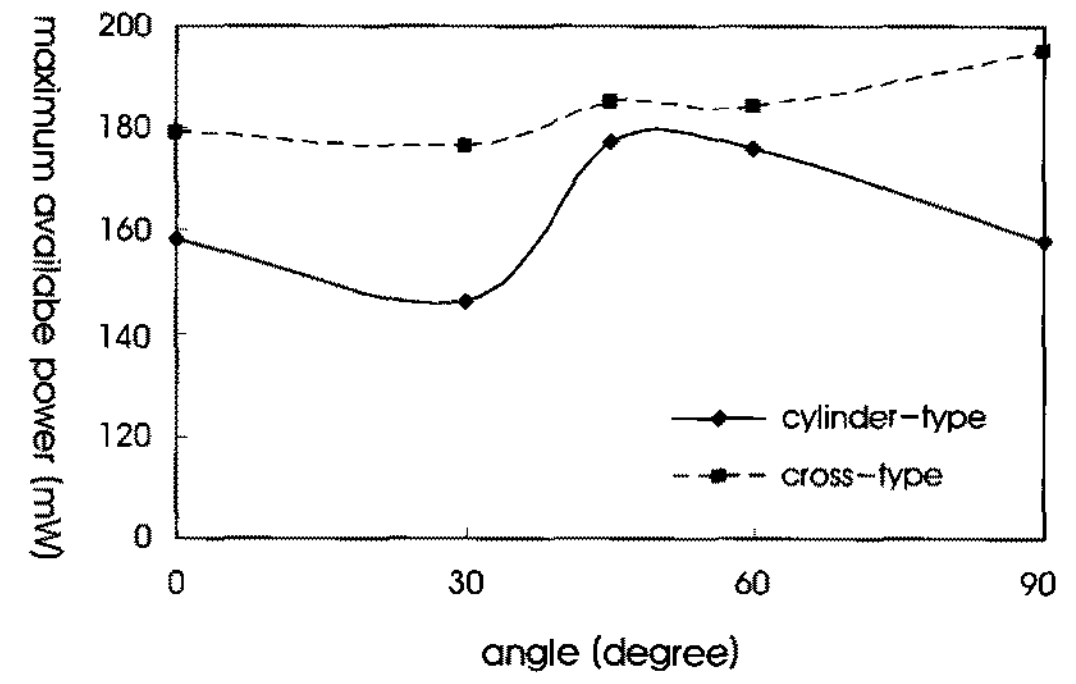

Fig. 7. The deliverable power variations of 2-dimensional receivers according to the orientation angle.

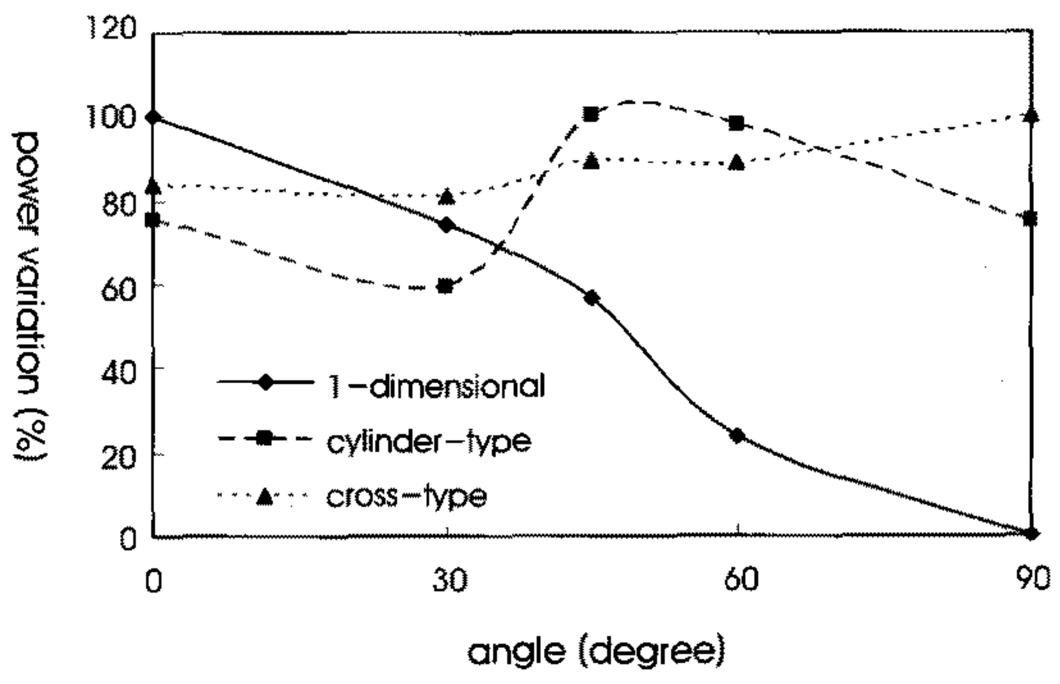

Fig. 8. The power variations relative to the maximum of 2-dimensional receivers according to the orientation angle.

distortion of the rectified voltage signal when any of the coils was not aligned to the magnetic field. The coupling of the coils and the nonlinearity of the ferrites might involve this occurrence. And these phenomena seem to be stronger for the cross-type, resulting more homogeneous response.

It was difficult to compare the efficiency of space occupancy of each antenna construction. The cross-type wasted more spaces for slightly fat coils, but the diameter of the given space was bigger by 2 mm. The circular PCB for the cross-type was 50 % larger than that for the cylinder-type (10 mm vs. 8 mm). However the arrangement of the electronic components for the cross-type was more difficult because the one of the coils touching the board was fatter. The choice of the components was also important as much as their arrangement. Both of two parameters should be considered for the comparison of the spatial efficiency. On the contrary, the assembly with the cross-type antenna was obviously easier than with the cylinder-type. As its power variation characteristic was also better, the cross-type antenna was preferable for the 2D lateral antenna.

Ⅳ. CONCLUSION

This paper proposed multi-dimensional receivers to provide stable wireless power regardless of the orientation of the in vivo robotic capsule, which moves along the intestines. Two types of two dimensional antenna constructions were implemented and evaluated. One was winding coils on the external surface of the given space and inserting the employed ferrites in the space (the cylinder-type). And the other was winding them directly on the ferrites (the cross-type). Among them, the cross-type construction provided the easier assembly and could deliver more homogeneous power. It could deliver over 80 % of the possible maximum power against its orientation. Resultantly, the cross-type construction for the 2D lateral antenna was preferable in terms of the homogeneity and the assembly.

The proposed power receiver can be applied to any kind of in vivo robotic machines whose orientations are intrinsically undetermined, even though the proposed power receiver is targeting the development for the locomotive endoscope capsule.

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