Development of transcutaneous energy transmission system for totally implantable internal artificial organ systems

H. Miura, T. Shiga, H. Matsuki, and T. Yambe

***Abstract*— Newly designed transcutaneous energy transmission system for totally implantable internal artificial organ systems was developed. We obtained higher dc-dc efficiency of 93.4% and smaller size 33ml of devices. Also, the devices were designed in view of the biomedical compatibility; gradually sloped coils and the flexibility of the primary coil prevent pressure necrosis of the skin. The rectifier circuit board was placed in the internal space of the ferrite core to reduce the number of the implanted devices. However, radiated outward ground patterns were adopted to achieve a balance between thermal radiation and reduction of eddy-current loss.**

I. INTRODUCTION

Heart transplantation is currently the best treatment forvend-stage heart failure. There is a large disparity between the number of available donor hearts and the number of people who need them. Total artificial hearts and ventricular assist devices have been developed as alternatives to the transplantation. Percutaneous leads should be avoided in long-term implantations due to the risk of infection and the restraint on patients' activities, transcutaneous energy transmission systems (TETS) was propesed [1]. We have developed TETS for the undulation pump ventricular assist device (UPVAD) [2] and other totally implantable internal artificial organs. TETSs that were clinically used or under development had air cored coils and conventional diode rectifiers. Our system has thin ferrite cores, which increase the magnetic coupling factor and self-inductance. In addition MOSFET synchronous rectifier can reduce forward voltage drops. These features result in high-energy transmission efficiency. The system achieved the dc-dc maximum efficiency more than 90%. We developed a synchronous rectifier using a digital phase-locked loop (PLL) technique [3], which eliminated the resonant capacitor and the smoothing inductor used in the resonant technique [4]. Also, the core has a roll of magnetic shield. This effect made it possible to mount the synchronous rectifier circuit board on the back of the coil. Thus, the number of the implanted devices and the volume of the device were reduced. We can use much smaller and more flexible interconnection cable instead of the Litz wire that is stiff and has a large diameter. In animal experiments, the output voltage of the TETS decreased when the primary coil shifted from the normal position. Local elevations of temperature at voltage regulators that consume relatively high power caused heat injuries. Also, pressure necroses were seen in the circumference of the secondary coil. The size of the coil is 90 mm diameter and 10 mm thick, which is still large for implantation.

II. METHODS

In Fig. 1, the circuit of the TETS is shown. The inverter consists of full-bridged MOSFETs and drives the primary coil at the fixed frequency of 160 kHz. The waveform of the inverter's output voltage is rectangular. A resonant capacitor is inserted in series so that the internal impedance is minimized at a 15mm coil distance [5]. Reduction in the number of the electrical devices in the synchronous rectifier circuit was achieved by adoption of the double-ended topology instead of the full-bridged topology used in the former edition. Then electrical devices are placed in the internal space of the circular truncated corn ferrite core (Fig. 2, 3).

The rectifier board was designed to achieve a balance between thermal radiation and reduction of eddy-current losses. Pairs of the gate control ICs, Schottkey barrier diodes (SBD) and MOSFETs were placed symmetrically with respect to the center of the circuit board. They are placed at the points of a regular hexagon. It is best to use a solid ground plane so that we can obtain the minimum ground impedance and thermal uniformity. However, in spite of the utilization of the ferrite core, the leakage magnetic flux caused the heat generation at the solid ground plane. In order to release the heat of the devices and prevent eddy-current losses, radiated-outward ground lines were designed. The circuit board is 50 mm in diameter. The diameter and the thickness of the internal device were reduced to 72 and 9 mm, respectively. The numbers of turns for the primary and secondary coils were 18 and 9, respectively. The inner and outer diameter of the secondary coil was 36 and 70 mm and the secondary coil had 17 degrees slope. A Litz wire of 280 x 0.08 mm was used to reduce skin effect, where the one of 200 x 0.12 mm was used in the previous primary and secondary coils. They were molded with the epoxy resin. The primary coil and its thin Mn-Zn ferrite chip core were molded with the silicon rubber. This results in the flexibility and prevention of pressure necroses. Inner and outer diameters of the primary coil are 50 and 90 mm, and the primary coil had 10 degrees slope. A Litz wire of 320 x 0.08 mm was used.

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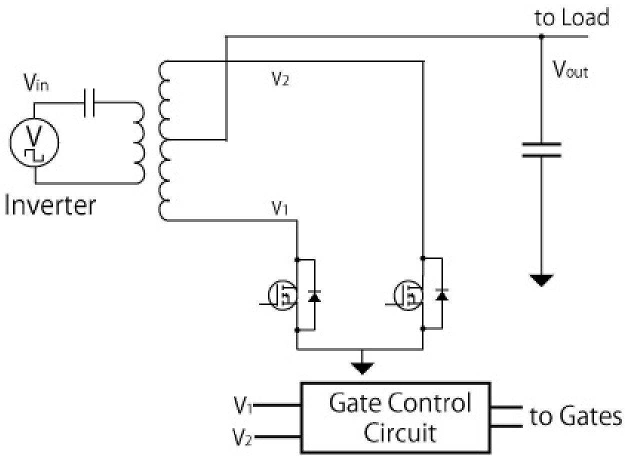

Fig.1 Simplified circuit diagram of the TETS

III. RESULT

The temperature rise of the circuit board was measured alone by infrared thermograph in the room air. The ambient temperature was 24.5 C, and the output voltage and current were 10.7V and 2.5 A. The maximum temperature of 36.8 ℃ was measured at the place where the MOSFET located. On the other hands, conventional SBD rectification temperature raised more than 65 ℃. The board was placed on a wooden desk horizontally (Fig. 5). Because thermal conductivity of cupper is much greater than that of glass-fiber reinforced plastic printed circuit board (FR4), heat was released along radial direction rather than circular direction. However, sufficient thermal uniformity was not obtained. We measured load characteristics of newly developed TETS *in vitro*. The input voltage was set to 18.5 V assuming that a 5-cells Li-ion battery was used. The maximum efficiency was calculated from the measured dc input voltage and current of the inverter, dc output voltage, and current of the rectifier circuit. Dc-dc load characteristics are shown in figs. 6, 7, and 8. The output voltage was stable at 15 mm, while output voltage decrease drastically at 0 mm because of increase of internal impedance. The maximum efficiency at 0 mm and 5 mm are the same as 93.4%, the maximum efficiency of the transformer increases as the coupling factor increases or the distance decreases. However, in this measurement the efficiency involves the switching loss, resistance of MOSFET and diodes' forward drop during transition periods. These nonlinearities tend to reduce efficiency and output power when the output voltage is low and the output current is high. There was no significant difference whether placing the circuit board in the ferrite core or not. We evaluated the system *in vivo*; the internal unit was implanted to the goat model, and a load characteristic was measured. Maximum efficiency was the same as the *in vitro* measurement 93.4%. Distribution of maximum output current of the transcutaneous energy transmission system is shown in fig.9, the system could be used in range of ±15mm radial miss arrangement and within 15 mm coil spacing g. Also, distribution of maximum efficiency of the transcutaneous energy transmission system is shown in fig.10, this system kept the transmission efficiency high in the wide area.


Fig.2 Developed transcutaneous energy transmission system for totally implantable internal artificial organs.
Left; Primary (outside the body) coil, the outer diameter is10mm. Right; Secondary (inside the body) coil, the outer diameter is 72mm.

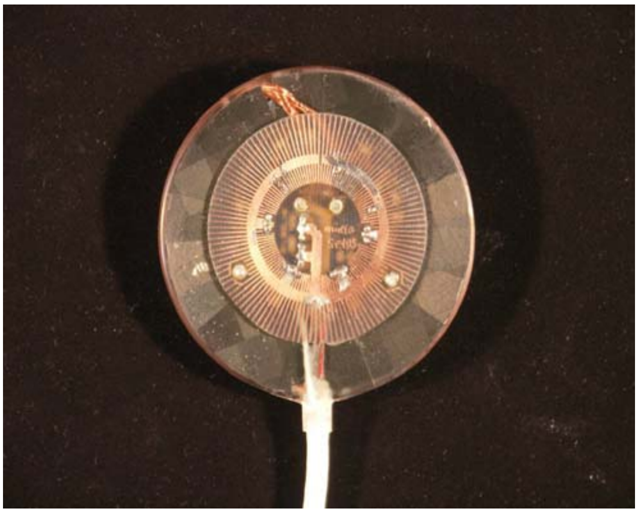
Fig.3 Back side of the internal coil

Synchronous rectifier circuit mounted in the back of the internal coil.

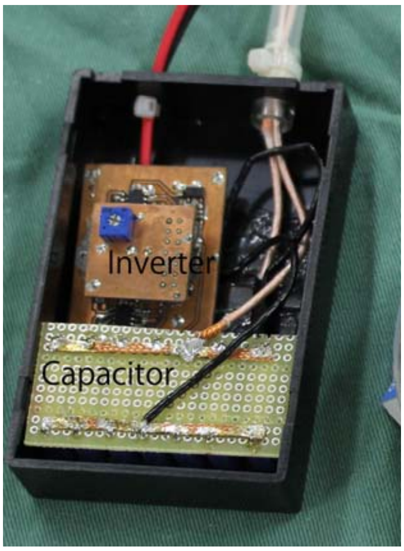

Fig.4 Inverter Unit

Coil driving inverter unit, which consists of CR multi vibe oscillator, MOSFET full bridge inverter and compensation capacitor.

IV. DISCUSSION

We succeeded in the miniaturization and the efficiency improvement. The size of the internal unit was small enough so that the size was almost same as the implantable defibrillators. We confirmed that the system could transmit up to 45W. The system can be applied to various kinds of totally implantable internal artificial organ systems [6]. Artificial heart system with TETS is not available today [7], [8]. However rotary blood pumps have much small power consumption, it is much easy to realize total implantable system with them. Synchronous rectifier is good for reduction of temperature rise, however, the risk of failure is severe and use of conventional diodes rectifier must be considered with improvement and evaluation of the heat dissipation capacity. Our design of coil shape [9], and leakage compensation system were optimized for non-feedback operation, however we are examining control methods, which changes driving frequency depending on the primary side current phase, not on the signal transmission system [10] for stabilization of the output voltage. We continue research and development for clinical use in aspect of safety, especially use of Li –ion batteries.

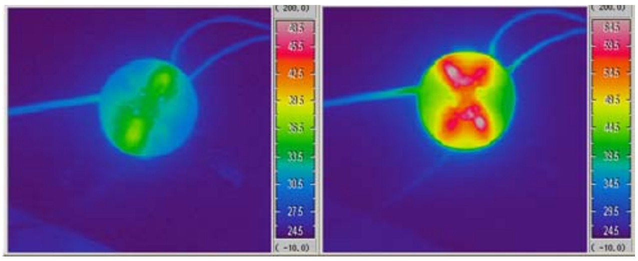

Fig.5 Thermography of the rectifier board
Synchronous rectification (left), SDB rectification (right). the output current was set to 2.5A.

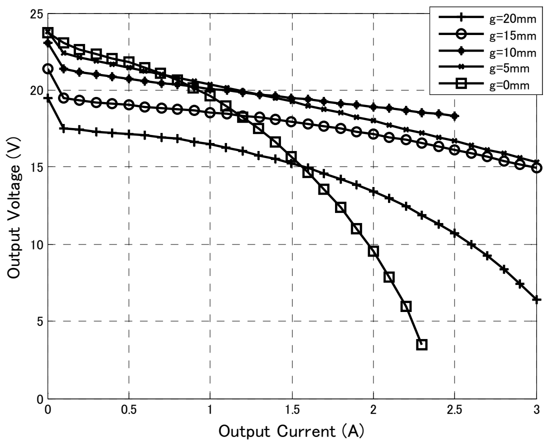

Fig.6 Output current vs. output voltage

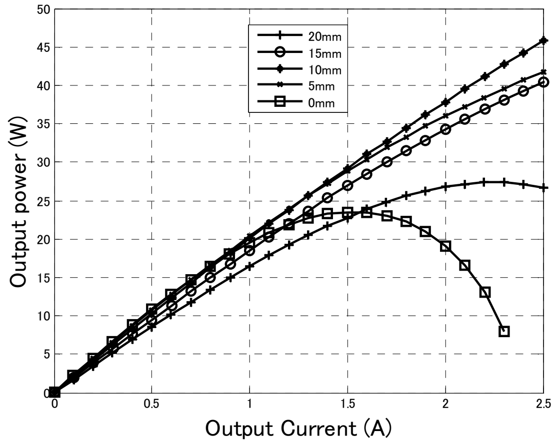

Fig.7 Output current vs. output power

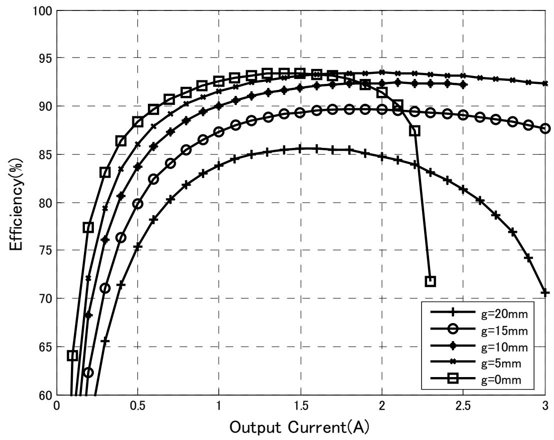

Fig.8 Output current vs. transmission efficiency

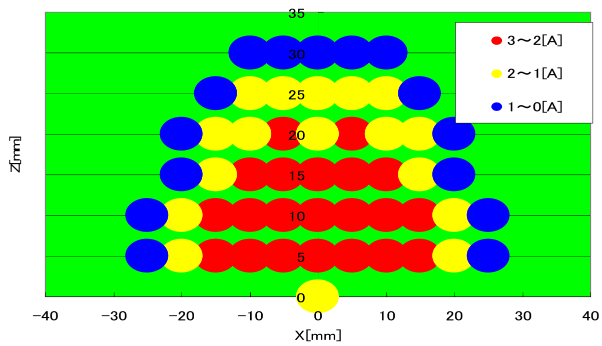

Fig. 9 Distribution of maximum output current of the transcutaneous energy transmission system

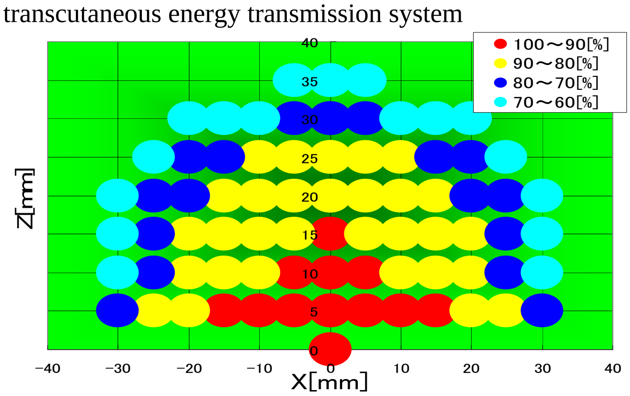

Fig.10 Distribution of maximum efficiency of the transcutaneous energy transmission system

V. CONCLUSION

A newly designed transcutaneous energy transmission system was developed. We succeeded in the miniaturization and the efficiency improvement to 93.4%. We confirmed that the system could transmit enough energy to drive UPVAD and could be applied to totally implantable internal artificial organ systems.

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