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Wireless Energy Transfer Platform for Medical Sensors and Implantable Devices

Fei Zhang, Steven A. Hackworth, Xiaoyu Liu, Haiyan Chen, Robert J. Sclabassi, and Mingui Sun

***Abstract*—Witricity is a newly developed technique for wireless energy transfer. This paper presents a frequency adjustable witricity system to power medical sensors and implantable devices. New witricity resonators are designed for both energy transmission and reception. A prototype platform is described, including an RF power source, two resonators with new structures, and inductively coupled input and output stages. *In vitro* experiments, both in open air and using a human head phantom consisting of simulated tissues, are employed to verify the feasibility of this platform. An animal model is utilized to evaluate *in vivo* energy transfer within the body of a laboratory pig. Our experiments indicate that witricity is an effective new tool for providing a variety of medical sensors and devices with power.**

I. Introduction

DESPITE the wide applications of noninvasive or implantable electronic devices in medical diagnosis and treatment, supplying electric power to these devices is a challenging problem [1-3]. The existing wired and wireless methods, such as the use of primary and secondary coils [1,2], are far from ideal due to the problems of inconvenience, low efficiency, and/or short range. There is a strong demand for novel power transmission technologies to support wireless medical sensors and devices.

Recently, a new wireless power transfer technique, commonly called witricity (wireless electricity), was reported in *Science* [4]. Distinct from electromagnetic induction, this technique utilizes the powerful mechanism of strongly coupled magnetic resonance to transmit power efficiently over a mid-range distance (a few times the resonator size). An intuitive but powerful concept is employed, i.e., two objects with the same intrinsic resonant frequency exchange energy efficiently, while two non-resonant objects exchange little energy. Using witricity, a 60 W light bulb was illuminated over two meters with an efficiency of approximately 40%. Two identical coil resonators, 60 cm in diameter, were utilized in this experiment. [4].

The coil resonator design in [4] aimed at validating the witricity theory. This design has limited practical applications because of its size, shape, unsteady structure and leakage of electric fields. In this paper, we investigate the witricity concept specifically for medical applications, aiming at developing a wireless energy supply platform for medical sensors and implantable devices.

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The authors are with Laboratory for Computational Neuroscience, Departments of Neurosurgery, Electrical Engineering and Bioengineering, University of Pittsburgh, Pittsburgh, PA 15260, USA. (Correspondence should be sent to M. Sun. Tel: 1-412-802-6481; Fax:1-412-802-6785; Email: drsun@pitt.edu).

II. Review of Witricity Theory

As shown in Fig. 1, the typical witricity system consists of an RF power source ("Oscillator"), load, two resonators ("Source" and "Device"), a driving loop, and an output loop. The RF power source provides energy for the system via the driving loop. This loop is coupled inductively with the source resonator which transmits energy magnetically over a distance to the device resonator. The device resonator is coupled inductively with the output loop which is connected to the load of the system.

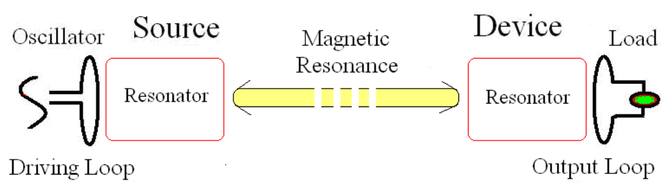


Fig. 1. Basic components of witricity system.

As discussed in [4-8], the conventional electromagnetic induction method for transmitting energy is inefficient over distances greater than the device characteristic size. The witricity method improves energy transfer efficiency by using the concept of strongly coupled magnetic resonance. This powerful mechanism effectively "tunnels" magnetic fields between the source resonator and the device resonator. This enables the device resonator to capture energy efficiently from the fields, even over a relatively far distance. The basic principle of operation is that, if two resonators are in mid-range proximity, their near fields (evanescent waves) will strongly couple with each other. This coupling allows the energy focused in a specific resonant frequency to transfer from one resonator to the other within a much shorter time than the characteristic decay time of the system [5-7]. Using this principle, the energy-transfer efficiency is significantly improved.

With the help of low-loss resonators of identical natural frequencies, high-performance mid-range wireless energy transfer systems can be built. Because the field wavelength is much larger than the diameter of the resonators and there is a tunneling effect as described previously, the magnetic fields between the resonators can follow a spatial curve and thus the line-of-sight requirement in many existing energy transfer methods can be eliminated. Another attractive feature is that magnetic fields interact with living organisms only weakly [4-5], making witricity a relatively safer method for energy transfer than the RF methods which involve interactions of both electric and magnetic fields with biological tissue.

III. Design of Witricity Resonators

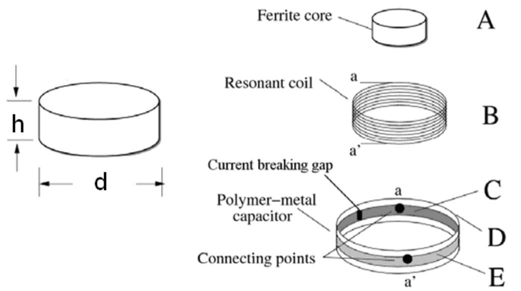


Fig. 2. Design of the resonant cell for use in witricity.

In theory, if the source and device resonators have the same natural frequency, any resonant LC tank circuit can be used in the witricity system including the simple coil design in [4] and the thin-film designs that we have reported [7,8,9]. Here we provide a design of a resonant cell for medical applications where the resonant frequency is adjustable. The cylindrical disassembled views of this design are shown in Fig. 2. Three cylindrical components (labeled A through E) are layered vertically in a concentric fashion. The inner-most part, A, is a thin ferromagnetic core which can be used to change the inductance of the coil B made of metal wire wound in a spring-like fashion. It is coated with a thin polymer film for insulation and compressed into a low-height cylindrical coil. Metal half-ring (C and E) sheets form a capacitor with thin polymer ring sheet D. The overlapping area of the two half-ring metal sheets can be changed to obtain different capacitances. Obviously, the adjustable resonant frequency of this LC resonator is determined by the tunable capacitance and inductance. The space-saving coil connects to the capacitor components directly via connection points *a* and *a'*, a novel wire-free design which keeps the resistance within the LC resonant tank circuit small. Note that some non-essential components, e.g., fixtures and insulating sheets between components, are omitted in the figure.

As discussed above, though both inductor and capacitor are changeable, practical considerations are taken for sake of feasibility. Specifically, for the source resonator of our witricity system, only the capacitor is tunable. Metal half-ring (C and E) sheets are affixed to both internal sides of two thin overlapped polymer ring sheets D. The two half-rings can move against one another, adjusting the capacitive area.

For the device resonator of our witricity system, one or more thin ferromagnetic cores are placed inside the coil to change its inductance. In this way, the resonant frequency of the device resonator can be adjusted, even though the capacitor, formed directly by affixing two open-loop metal sheets (C and E) on both sides of one layer of polymer ring (D) with maximized overlapping area, is fixed. We choose to maximize the capacitance of the device resonator because its size is usually small. The use of the maximum capacitance is often desirable in this case to achieve a resonant frequency which is not too high. In order to prevent any undesirable loop currents within metal ring C or E, open gaps are intentionally made in the two rings to break such current. This contributes to a lower energy loss and a higher energy transfer efficiency.

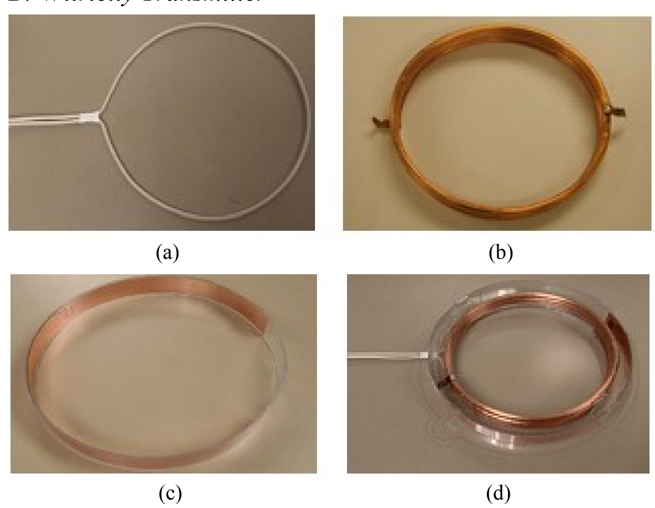
IV. Construction of Witricity Platform

Our witricity prototype consists of four main parts: RF power source, transmitter, receiver and load.

A. RF Power Source and Load

The RF power source utilizes an Agilent 33250 function generator, a DC power supply and a Class-AB RF power amplifier based on two BLF177 MOSFETs. An RF signal from the function generator is amplified via the power amplifier, which is powered by the DC power supply and linked to the driving loop in order to supply power to the whole system. In order to demonstrate the system's operation, we use a LED connected to the output loop as the load, simulating the loading effects of electronic circuits.

B. Witricity Transmitter



(a) (b) (c) (d)

Fig. 3. Main components of witricity transmitter: (a) driving coil (b)main coil (c)adjustable capacitor (d)combined system.

Following the design described in section III, we constructed a compact witricity transmitter, shown in Fig. 3. Our transmitter prototype consists of a driving coil (Fig. 3a), a main coil made of a copper pipe (165 mm in diameter) coated with epoxy (Fig. 3b) and an adjustable capacitor made of two rings of polymer sheets (not distinguishable in Fig. 3c as the two rings are appressed and transparent). Copper foil is adhered to the internal side of each sheet covering about 50% of the ring. The capacitance of this particular design can vary by a factor of four, providing adjustability of the resonant frequency of the source resonator. The main coil and this capacitor form the actual frequency configurable source resonator. Our design has a low profile (height only 25 mm) and is structurally suitable for practical applications.

C. Witricity Receiver

Similarly, we have also constructed a Witricity prototype receiver (Fig. 4) consisting of two main components: a tunable device resonator (Fig. 4a) and an output loop linked to a LED load (Fig. 4b). The resonator is composed of a silver coil (41 mm in diameter), a capacitor made with thin silver sheets, and removable ferromagnetic disc cores which are used to change the inductance and thus tune the resonant frequency. Silver, with its high conductivity, is used in order to reduce resistive losses.

Our design has a highly desirable property of reducing electrical field exposure in the vicinity of the resonator, due to almost all electrical fields being confined to the physical capacitor. This design helps to reduce safety concerns since the human body and many other conductive objects interact much more strongly with electric fields than with magnetic fields. Given the amount of transferred power, this also improves efficiency due to the decreased power absorption by other objects. In contrast, the design in [4] depends on distributed capacitances in a physical coil which results in a larger electric field exposure in the vicinity of the resonator.

V. Experimental Results

A. In Vitro Experiments

In our first experiment, the witricity transmitter was placed on top of a workbench and the receiver was affixed to a long plexiglass bar attached to an adjustable stand. Fine-tuning the variable capacitor, we made the witricity transmitter operate at around 6.9 MHz, as measured with a Vector Network Analyzer (8753ES), to match the resonant frequency of the receiver with a thin ferromagnetic core. We utilized a LED to provide visual testing feedback, as shown in Fig. 5a.

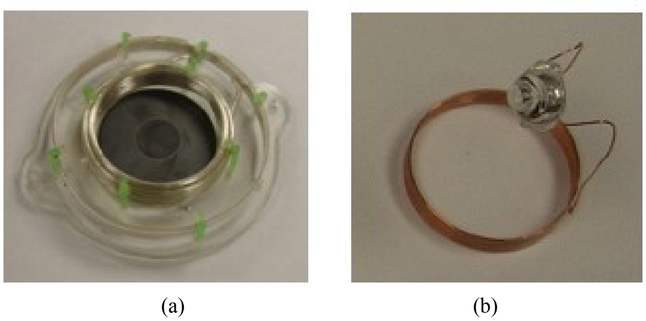


Fig. 4. Main components of witricity receiver: (a) combined resonator (b) output loop & LED load.

In order to demonstrate the feasibility of witricity for implantable devices, we implanted our receiver within the plastic skull head model in Fig. 5b. The inside of this skull model is filled with an agar solution (16 grams of dry agar, 0.9 liter of water and 0.6 gram of *NaCl*) as shown in Fig. 5c. This solution, after it consolidates, has similar electrical properties to the human brain with an average conductivity of approximately 0.21 *S/m*. The center of the agar "brain" was removed, forming a chamber within which our witricity receiving resonator was implanted (Fig. 5d). The chamber was covered with a round agar cover. The load LED on top of the head model was connected to the port of the output coil via two small holes through the skull. As seen in Fig. 5b, the LED glows at approximately the same brightness in the phantom head system as it does in the open air with the same power input. Compare panels (a) and (b) in Fig. 5.

For the convenience of utilization, we removed the thin ferromagnetic core and tuned the frequency of our system to 7 MHz. In order to obtain quantitative power transfer efficiency, we replaced the LED with a 1.5-kilo-ohm resistor whose resistance approximates the impedance of the output terminals at resonance. The powers at the terminals of the driving loop and the output loop were measured with a Schottky diode-based RF detector. The obtained power transfer efficiencies at different separation distances are shown in Fig. 6. At a transmitter-receiver separation of 90 mm, the energy transfer efficiency was found to be 22.3%. Although this efficiency is lower than that obtained by the existing system [1], our prototype witricity receiver is over one order of magnitude smaller (41 mm vs. 600 mm in diameter).

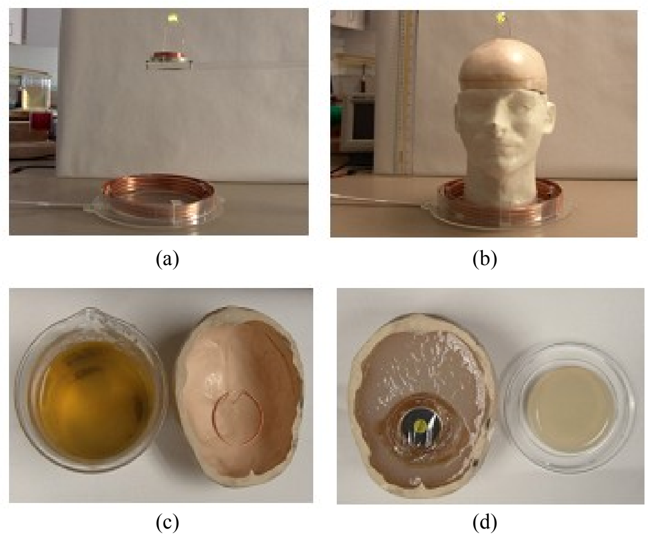


Fig. 5. *In vitro* witricity system: (a) through the air (b) through the head model (c) agar solution and internal view of head model (d) receiver implanted in "brain" and the agar cover.

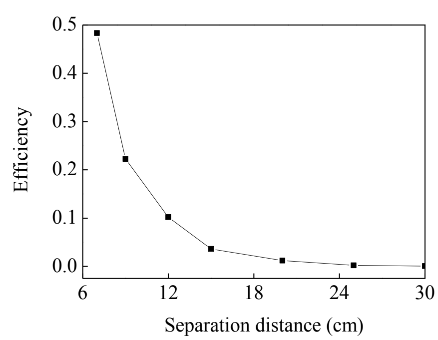
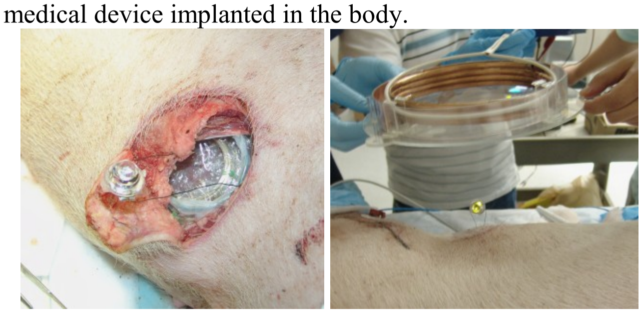


Fig. 6. Measured power efficiencies at different separation distances.

B. In Vivo Experiments

With IACUC approval, in a separate experiment conducted at the Animal Research Facility of the University of Pittsburgh, we evaluated *in vivo* energy transfer performance within the body of a Yorkshire pig (20 kg). During the experiment, life support was provided with general anesthesia.

An incision of approximately seven centimeters was made in the lower abdomen. The receiving resonator shown in Fig. 4a, sealed within a plastic bag, was implanted within the abdomen approximately 35 mm under the skin. After the skin and connective tissues were sutured, we successfully transmitted power to the implanted receiver from a distance of up to 100 mm, as evidenced by the illumination of a protruding LED. Fig. 7 shows the experimental setup and power transfer. If the LED is replaced by a rectification and regulation circuit, the power produced can be stored or used to directly operate a medical device implanted in the body.



(a) (b)

Fig. 7. Animal experiment on a laboratory pig: (a) implantation of our receiver (b) power transfer to implanted receiver.

VI. Discussions on Potential Medical Applications

In the medical field, microelectronic devices can be implanted within the human body to perform a variety of therapeutic, prosthetic, and diagnostic functions. Deep brain stimulation (DBS) devices, for example, are used as brain implants for treating Parkinson's disease and essential tremor. With our designed witricity platform, a recharging process can be performed at night by a device mounted on the headboard. This could reduce the size of the implanted battery and eliminate the need for battery replacement surgeries. Likewise, in virtue of the high efficiency characteristics of witricity, the external recharging system for implants such as an artificial heart can be conveniently incorporated into clothes or mounted on the back of a chair, instead of requiring the use of a recharging device placed on, or close to, the skin.

Another important medical problem of high interest is the design of a wireless body sensor network. Future wireless sensors can be patched on the skin or the clothes and powered by witricity using a single source resonator. The high significance of the body sensor network has been recognized by both the research community and industry. In order to further improve witricity, we have developed several types of thin film witricity resonant cells [7,8, 9]. We have also shown that these cells have several resonant frequencies due to their unique structure involving multiple conductor strips [8]. Hence it becomes possible to achieve simultaneous power transfer and communication by utilizing different resonant frequencies of a single resonator. This allows device size to be reduced while maintaining full functionality, a very attractive property for medical devices and body sensor networks.

VII. Conclusions

Based on recently proposed wireless energy transfer technology (witricity), we have presented a frequency configurable platform to wirelessly transmit energy for medical implants and sensors. Our prototype designs and experiments through both simulated and real biological objects have shown that witricity is a powerful technology for a variety of future medical applications.

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References

[1] S. Suzuki, T. Katane, H. Saotome and O. Saito, "Electric power generating system using magnetic coupling for deeply implanted medical electronics devices", *IEEE Trans. Magnetic*, vol. 38, pp. 3006-3008, Sep. 2002

[2] R. Puers and G. Vandevoorde, "Recent progress on transcutaneous energy transfer for total artificial heart system", *Artificial Organs*, Vol. 25, No.5, pp.400-405, 2001

[3] Z. Tang, R. J. Sclabassi, C. Sun, S. A. Hackworth, J. Zhao, X. Cui, and M. Sun, "Transcutaneous Battery Recharging By Volume Conduction and its Circuit Modeling," *in IEEE Int. Conf. of Eng. in Medicine and Biology Society*, pp. 644-647, Sep. 2006

[4] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, pp. 83-86, Jul. 2007

[5] A.Karalis; J.D. Joannopoulos, and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer," *Annals of Physics*, vol. 323, , pp. 34-48, Jan. 2008

[6] W. Stewart, "The Power to Set You Free", *Science*, Vol.317, pp. 55-56, Jul. 2007

[7] F. Zhang, X. Liu, S. A. Hackworth, R. J. Sclabassi, and M. Sun, "*In Vitro* and *In Vivo* Studies on Wireless Powering of Medical Sensors and Implantable Devices", *IEEE-NIH 2009 Life Science Systems and Applications Workshop,* Bethesda, Maryland, USA, Apr. 9-10, 2009,

[8] X. Liu, F. Zhang, S. A. Hackworth, R. J. Sclabassi, and M. Sun, "Modeling and Simulation of a Thin Film Cell for Power Transfer to Medical Devices and Implants", *IEEE Int. Symposium on Circuits and Systems*, May 24-27, 2009, Taipei, Taiwan.

[9] X. Liu, F. Zhang, S. A. Hackworth, R. J. Sclabassi, and M. Sun, "Wireless Power Transfer System Design for Implanted and Worn Devices," 35th IEEE Northeast Biomedical Engineering Conference, Boston, Cambridge, MA, USA, April 3-5, 2009.