Ultrasonically Powered Hydrogel-Based Wireless Implantable Glucose Sensor

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Abstract—**This paper reports on the development of a wireless ultrasound (acoustic) powering technique for an implantable glucose sensor. The acoustic power transmission system consists of a pair of PZT transducers, and is capable of providing the power and voltage required by the glucose sensor. A piezoelectric receiver with a diameter of 12.7 mm, and a PZT transmitter operating at 800 kHz are employed. The hydrogel-based glucose sensor requires a DC voltage of 200 mV. The output AC voltage of the receiver should be rectified before going to the sensor. A wireless inductive sensing technique is employed for the low power hydrogel-based implantable glucose sensor. The glucose test results show that the proposed system is capable of sensing the glucose changes within the physiological range.**

Keywords—acoustic power transfer; medical implantable devices; glucose sensor

I. Introduction

The prevalence of diabetes mellitus and obesity are rapidly increasing in the United States as well as in the rest of the world. It has been convincingly demonstrated both for type 1 and type 2 diabetes that tight control of blood glucose concentrations will prevent and/or delay the onset of these tragic complications [1]. An implantable glucose sensor permits diabetics to obtain real-time, accurate glucose readings without pricking their finger. Implanted medical devices are most often powered by a battery [2], near field electromagnetic energy transfer [3], or mid- to far-field electromagnetic (i.e. RF) [4] energy transfer. As the size of implanted devices has continued to shrink, especially in the case of biosensors, power transfer has become an increasingly significant problem [5]. The efficiency of electromagnetic and RF power transfer drops dramatically as the size decreases [6] due to the relatively large wavelength of electromagnetic waves and the increased attenuation at high frequencies.

Acoustic energy has much shorter wavelengths and its attenuation is relatively low in aqueous environments and human tissue compared to RF [7], [8]. Recently Denisov and Yeatman [9] have studied the theoretical limits of acoustic power transmission through tissue compared to the more standard electromagnetic approach. They have shown that for small sizes and large implant depths, acoustic power transmission can be an order of magnitude more efficient.

This paper presents the design of an ultrasonically powered wireless glucose sensing system. The key functionalities of the system with a slightly scaled up acoustic power generator are demonstrated. Fig. 1 depicts the proposed deeply-implantable wireless glucose sensing architecture, where a miniature sensor is implanted inside the human body and powered by an ultrasonic power source. The biochemical concentration inside the body can be sensed by an inductive sensing technique employing a functionalized hydrogel embedded with a miniature metallic plate [10]. Functionalized hydrogel can reversibly change in volume proportional to the change in the corresponding biochemical concentration. The volumetric changes displace the metallic plate. This displacement causes a change in inductance of a sensing coil placed in proximity, thus altering the resonance frequency of the oscillator circuit. This proposed sensing technique allows the sensing coil and electronics to be robustly encapsulated in a hermetically-sealed glass package because the sensing configuration obviates the need for a direct contact between the coil and hydrogel, which is attractive for long-term applications.

a)

b)

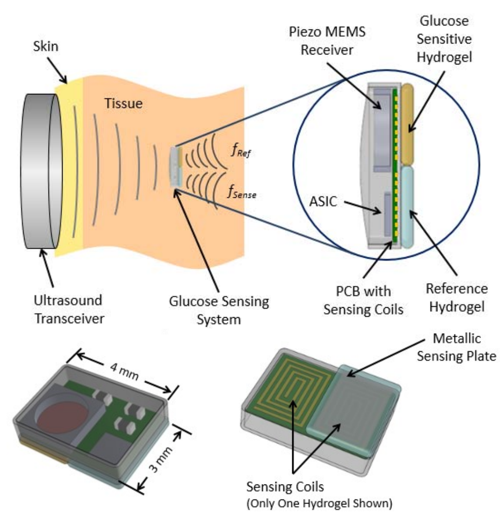

Fig. 1. Representation of the ultrasonic powered glucose sensor. (a) System representation and communications system with cross-section. (b) Isometric view of packaged implant.

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II. Acoustic Power Transmission

Fig. 2 depicts the experimental setup where a bulk-mode PZT disk is driven by a function generator at 800 kHz to power a 12.7 mm diameter, 1.9 mm thick, PZT receiver, through water. To obtain the experimental data, a 59 × 28 × 28 cm^3 tank with acoustic absorbers and transducers, shown in Fig. 2, was constructed. The acoustic absorber panels were fabricated from 12.7-mm-thick ultra-soft polyurethane (McMaster Carr; 8514K75). The efficiency of acoustic power transmission is first studied. Tests were run with a 20 V_{pp} input from a function generator (Rigol DG1022A) connected to a power amplifier (Rigol PA1011). Data were collected using a spectrum analyzer (PicoScope 2206). The RMS AC voltage generated is plotted versus the depth of the receiver, alignment and orientation of the receiver in Fig. 3-5, respectively. The receiver can have offset from the acoustic axis producing misalignment or have non-zero angle of orientation with respect to the transmitter face. According to these figures, and also due to the fact that the glucose sensor requires a DC voltage of 200 mV, the acoustic test setup is capable of producing voltage levels considerably higher than that required by the oscillator.

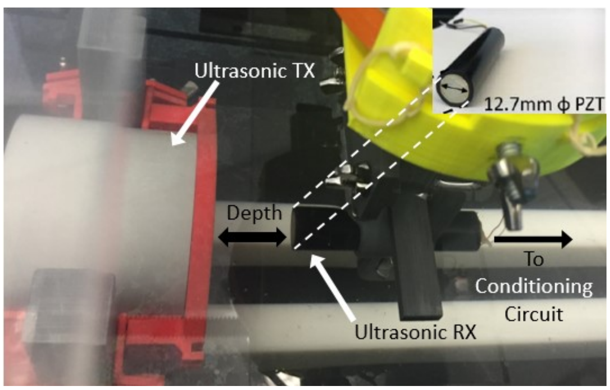

Fig. 2. Acoustic power transfer test setup.

The conditioning circuit shown in Fig. 6, consisting of a full-wave rectifier and LDO regulator, is used to provide a stable DC voltage. The rectified output voltage is 200 mV when the transmitter is driven with 20 V_{pp}. The rectified DC output powers a glucose oscillator-based biochemical sensor. The hydrogel and sensing coil are immersed in a separate testing solution tank to simplify the system demonstration. It should be noted that in this demonstration, the received acoustic power is far greater than the oscillator requires, indicating that the acoustic receiver can be significantly scaled down in size. When the offset and angle are zero, the receiver generates 12.4 mW.

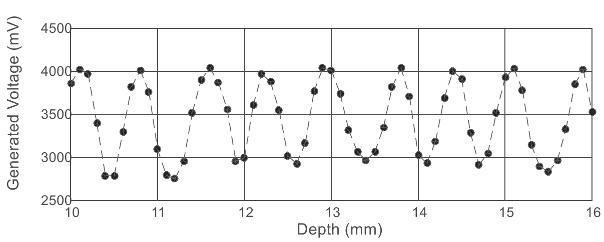

Fig. 3. Generated voltage versus depth of the receiver.

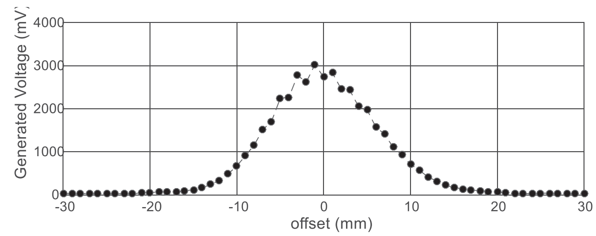

Fig. 4. Generated voltage versus lateral offset of the receiver.

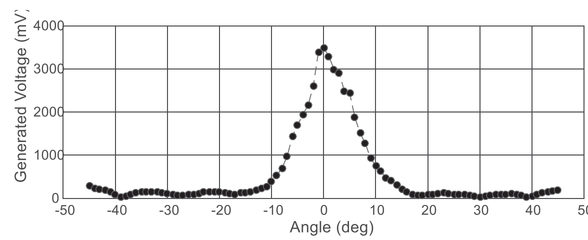

Fig. 5. Generated voltage versus angle of the receiver.

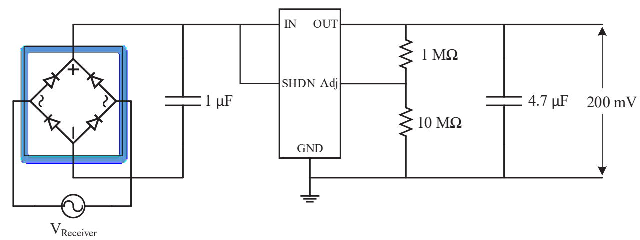

Fig. 6. Conditioning Circuit.

III. Wireless Hydrogel-Based Glucose Sensor

The experimental setup of the proposed glucose sensor is depicted in Fig. 7 where an 8 mm-diameter oscillator PCB was placed in a 3D-printed sensor package with a 2 mm-diameter-10-turn sensing coil in direct contact with the 80 µm-thick sensor package bottom plate. A 3 mm × 3 mm × 400 µm functionalized hydrogel sample embedded with a 3 mm × 3 mm sensing metallic plate was adhered onto a 3D-printed adjustable platform via gelbond film. Then the adjustable platform was assembled to the 3D-printed sensor package using screws, which were used to adjust the gap size between the sensing metallic plate and the package bottom plate to be approximately 50 µm. The package was sealed with PDMS and then coated with 10 µm parylene C as a biocompatible as well as moisture resistant layer. The sensor assembly was mounted to the lid of the testing container and submersed in 1xPBS solution with controlled glucose level for glucose testing.

A tunnel diode oscillator, where a commercial silicon tunnel diode is employed for the prototype oscillator design is shown in Fig. 8. The tunnel diode was biased at 200 mV to achieve a negative resistance of around -1500 Ω, sufficient to compensate the LC tank loss and therefore ensuring a stable oscillation. The tunnel diode consumes approximately 200 µA at 200 mV bias voltage, corresponding to a power dissipation of 40 µW.

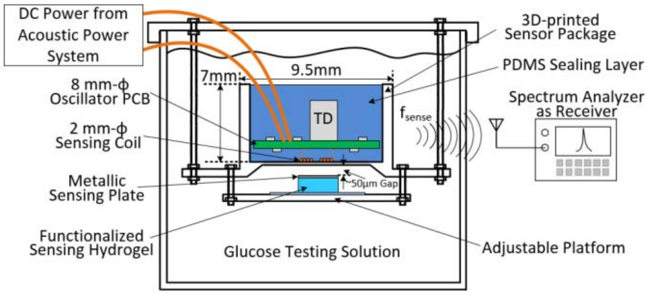

Fig. 7. In vitro wireless glucose sensor test setup.

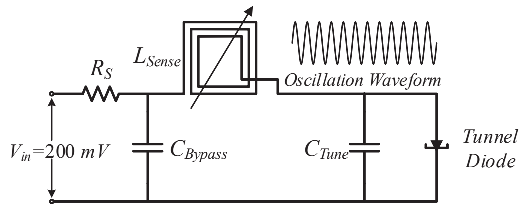

Fig. 8. Tunnel diode oscillator design topology.

IV. Acoustic Powered Glucose Testing Results

Fig. 9 depicts the full acoustically powered experimental setup. The sensor is submersed in 1xPBS solution with a glucose concentration of 0 mM. Then the glucose was ramped up to 10.5 mM with a 3.5 mM step change every 24 hours. The concentration is fixed at 10.5 mM for two days (48 hours) at the end of the test to investigate stability. To detect the oscillation frequency, as shown in Fig. 10, a receiver antenna is placed outside the testing container and 4 cm away from the sensing coil and is connected to a spectrum analyzer. The preliminary result of the acoustically powered glucose sensor is shown in Fig. 11. The general trend of the oscillator frequency can predict the change in glucose concentration although the response time is not short. As is evident during the last 48 hours of testing, the system exhibits some instability. Investigation of the source of this instability is ongoing.

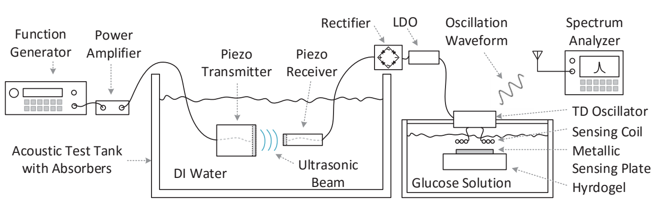

Fig. 9. Acoustically-powered wireless glucose sensor test setup.

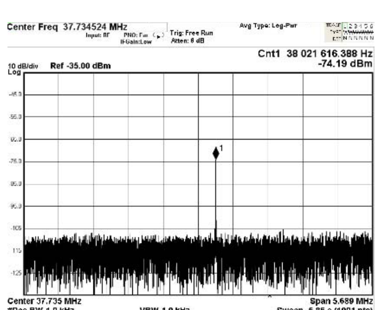

Fig. 10. Spectrum of wirelessly received osillator output power.

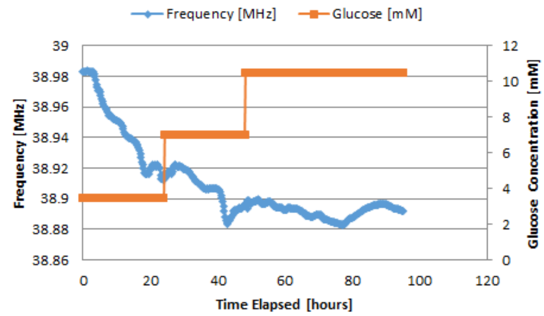

Fig. 11. Glucose test result.

V. Conclusion

An ultrasonically powered implantable glucose sensing system has been presented. The acoustic power transmission technique successfully demonstrates wireless power transmission. The glucose sensor requires a stable DC voltage which can be provided by acoustic power transfer. As the received voltage is an AC voltage, some power conditioning is needed to make it a stable DC voltage. The results show that the sensor can detect the change in glucose concentration. Future work aims to address the sensing frequency stability for longer periods of time.

Acknowledgment

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