Wireless Power Transfer for ECG Monitoring in Freely-Swimming Zebrafish

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***Abstract*— Zebrafish have proven to be a crucial model for biological elucidations, especially heart-disease studies, owing to their remarkable regeneration capacity. Other than conventional methods, monitoring of electrocardiogram (ECG) has shown promising results recently; however, experiments were usually carried out with sedated fish, resulting in affected signals. In this work, wireless power transfer (WPT) via inductive coupling is developed to power our previously-reported miniaturized ECG sensor implanted in an adult zebrafish. This would enable continuous monitoring of freely-swimming fish without disrupting their normal activities. The WPT is achieved using inductive coupling with the transmitter (TX) located around the fish tank, and a solenoid embedded in the fish implant as the receiver (RX), with sizes of *Φ*77 mm × 10 mm and *Φ*1 mm × 10 mm, respectively. Power transfer efficiency (PTE) and an adaptive tuning method were characterized using a Vector Network Analyzer (VNA) via S-parameter measurement to ensure the ECG sensor will receive sufficient power for operating and communication.**

Keywords—Wireless Power Transfer; Zebrafish; Electrocardiogram; Heart Regeneration; Backscattering

I. Introduction

Zebrafish (*Danio Rerio*) models continue to be an engaging topic in studies of regenerative medicine due to their capacity to fully regenerate after 20% ventricle amputation within two months [1]. Traditionally, biological studies are carried out with genetically-modified mutants, optical assessment of immunohistochemical slides, as well as DNA and protein analyses, in order to study the roles of various signaling pathways in cardiac development and regeneration [2]. Although possessing obvious advantages, those approaches failed in elucidating the progress of the process (i.e. regeneration and remodeling) of the same samples over time. Further, these studies cannot indicate the overall functionalities of myocardium under investigation. Recently, our team and others have successfully demonstrated ECG acquisition in zebrafish using microelectrode array (MEA) membranes [3], which provided favorable signal-to-noise ratio (SNR). The signals were distinguishable between heart-injured fish and shams; thus enabling a novel tool to investigate regenerating hearts. However, the fish were sedated and paralyzed while measurements were made, leading to non-intrinsic ECG data which were not relevant for studies.

WPT via inductive coupling has been demonstrated as the most reliable and efficient method to transfer energy to medical implants (IMDs) [4]. The IMD is often stationary or minimally mobile, thus the mutual coupling of the transmitter (TX) and receiver (RX) coils can be held around a constant. This, unfortunately is not the case with freely-moving small animals, such as zebrafish. For IMDs, a pair of planar antennas is widely used [5]; however, due to the limited area on zebrafish, a compact planar thin-film coil with a low quality factor (Q) would most likely not be able to harvest enough energy via inductive coupling to operate the sensor.

In this context, we develop a novel system of wireless power transfer (WPT) to power a compact ECG sensor membrane mounted on the fish body, such as the one described in [3], enabling continuous long-term monitoring of freely-swimming fish. The aim is to gather intrinsic ECG data without the need to remove the animal from its environment. The proposed system comprises two parts, the TX and RX units. The TX includes a customized cylinder-shaped fish tank which encloses the aquatic environment of the fish, the TX coil and electronics. The RX includes the ECG sensor, the RX coil and compact electronics. The solenoid approach helps minimize the misalignment issues which are critical to planar antennas [5]. The power transfer efficiency (PTE) of the overall system was optimized by continually adapting the transmission power frequency though a frequency tuning process reported previously [6]. Communication of the ECG data will be realized via load modulation as reported in [5]. Further, this way also enables simultaneous ECG monitoring of multiple fish housed in the same tank with some adjustment in the communication method, enhancing significantly the throughput of the system. However, this paper will focus on WPT characterization. The conceptual design of the entire system is illustrated in **Fig. 1**.

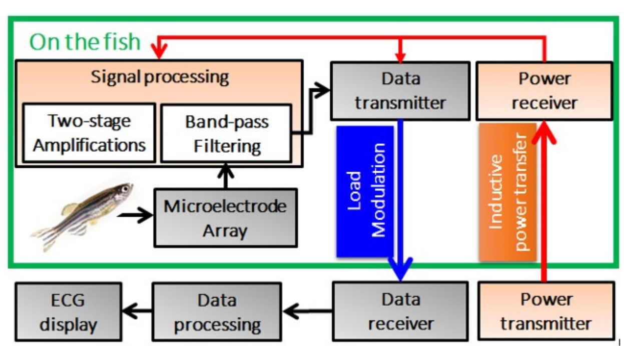

Fig. 1. Block diagram and conceptual design with WPT.

II. Design, Methods and Implementation

Based on our calculations, the minimum power that the ECG device (containing a differential amplifier, filters and possibly a multiplexer) needs will be 200−300 µW, and the carrier frequency of the power transmission should be around 1 to 30 MHz to minimize absorption by the water. Here, an operating frequency at ~13.56 MHz was chosen. Our WPT setup was based on the reported method of using an active drive coil and a passive resonant TX coil to transmit power [6]. The basic concept is that the drive loop is driven with a high magnitude AC current to generate a high magnitude alternating magnetic field which excites the TX coils that resonate at a particular frequency and couple with an RX tank. Ideally, the entire housing should have been covered by a number of TX coils to evenly distribute the field as well as to improve coupling, however, to demonstrate a proof-of-concept system, here, we built 4 identical TX passive LC tanks.

A. Transmitter and Receiver Design

The TX and RX coils were made in house. The customized cylindrical housing is a polycarbonate waterproof tank with dimensions *Φ*75 mm × 310 mm. On one side of the tank is a drive loop which excites four separate but identical TX coils symmetrically wrapped around either side of the housing. These four TX LC tanks resonate at a frequency of 13.56 MHz and couple with the RX coil (also tuned to 13.56 MHz). The TX and RX coils have dimensions of *Φ*77 mm × 10 mm and *Φ*1 mm × 10 mm, resulting in inductances of 208.9 µH and 0.15 µH, respectively. Thus, the capacitance values were calculated to be 0.659 pF and 918.9 pf for the TX and RX tanks, respectively. The TX and RX coils are showed in **Fig. 2.**

B. Frequency Tuning

Frequency auto-tuning for WPT via inductive coupling has been recently developed as a technology to maximize and stabilize PTE [6]. As the fish swims around, the RX coil moves around the tank and the mutual coupling of the coils changes. This change will result in a partially-reflected transmitted power. If we use a directional coupler on the drive coil to identify this reflected power, for a particular position and alignment of the RX coil, then its transmission frequency could be swept to find out the point at which the reflected power is minimal. This means that PTE could be optimized by probing around the set resonant frequency of 13.56 MHz in order to maximize the power received in the RX, and consequently maintaining a sufficient power in the implant to operate the system.

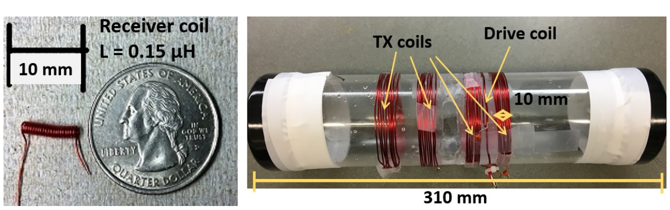

Fig. 2. TX coils, driver coil and housing (right) and RX coil (left).

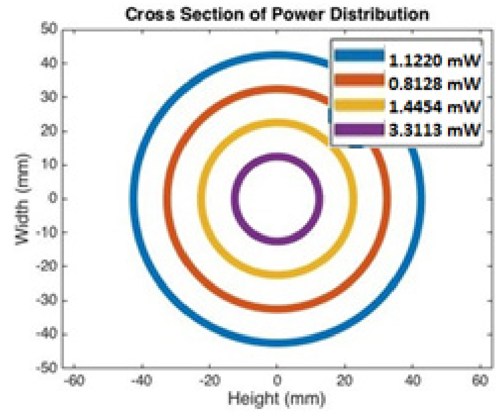

Fig. 3. Cross section of power distribution inside TX.

III. Experiments and Results

In order to characterize power distribution and PTE, S_{21} - the transmission coefficient was measured using a VNA (*8753ES*, *Agilent Technologies, Santa Clara, CA*).

A. Power Distribution

The experiment was performed to investigate the power distribution of the system at different radial distances from the center of the TX housing. As the RX solenoid was kept parallel to the TX solenoid, the PTE was measured at 4 different radial distances from the center of the solenoid; those were at 10 mm, 20 mm, 30 mm, and 40 mm. We assumed that, due to the symmetrical circular shape of a solenoidal cross-section, all points within that cross-section equidistant from the center would have the same PTE value. Using this information and with a nominated value for the transmitting power of 1W, we plotted the power transfer characteristics within a cross section of our TX, as seen in **Fig. 3.** We found out that as the radial distance increases, the power received at the RX remained fairly consistent, and therefore our customized housing with TX and RX coils and WPT scheme would provide stable sufficient power to the fish implant.

B. Pitch Efficiency and Frequency Tuning

Assuming the transmitting power is 1 W, in order to obtain at least 200 µW in the implant, the PTE should be above

$$10\log\left(\frac{200\,\mu W}{1\,W}\right) = -37\,dB \qquad (1)$$

for every possible orientation of the fish inside the cylindrical tank. Therefore, we have investigated the PTE between the TX and RX at varying degrees of misalignment for a complete 360° spectrum, incrementing by 10°. For each position, we measured the PTE at 13.56 MHz and then the highest possible PTE at that angle via the aforementioned frequency tuning method. As can be seen in **Fig. 4a,** the chosen frequency of 13.56 MHz was inside the high-PTE zone; however, there were larger ridges at ~10.18 MHz, with PTE values ranging from around -40 dB to -22 dB for 10.18 MHz and from around -60 dB to -34 dB for 13.56 MHz. The 2D PTE graph for both 13.56 MHz and 10.18 MHz is showed in **Fig. 4b** to further clarify the differences**.**

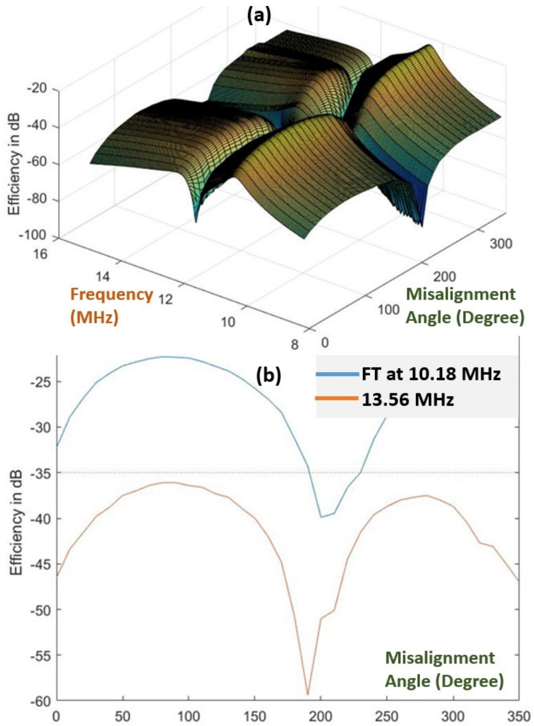

Fig. 4. (**a**) Dry tank 3D graph. (**b**) Dry tank PTE for both resonant frequency and tuned frequency (FT).

We then repeated the procedures with the cylindrical housing filled with tap water, and the results were shown in **Fig. 5.** PTE values were obtained ranging from around -57 dB to -34 dB at 13.56 MHz and around -45 dB to -25 dB at 10.18 MHz. As we can observe from both figures, with frequency tuning, the PTE stayed above -37 dB in most of the angles.

IV. Discussion and Conclusions

It can be seen that, by comparing **Figs. 5a** with **4a,** PTE stayed above the nominated -37 dB at a wider spectrum for the dry tank, which was due to the higher attenuation in water. We can see from **Fig. 5b** that the efficiency drops below -35 dB for misalignment angles of 20−50 degrees and 230−270 degrees, comprising 14% of all orientations. However, in practical scenarios, zebrafish are in constant motion, rarely holding one position for very long, thus our system would be guaranteed to successfully power the fish implant in most of the cases.

From our experiments, we found that it is possible to create an environment where magnetic field (and therefore power transfer) intensity is relatively constant in terms of position and where for most misalignment angles the power transfer is within the acceptable limit.

The system proposed in this work has been developed and characterized to address most prominent WPT issues of compact devices for small animal models. For future work, we will integrate the WPT and sensing part for the world's first ECG monitoring "jacket" that can pave the way to numerous bio-studies using the zebrafish model.

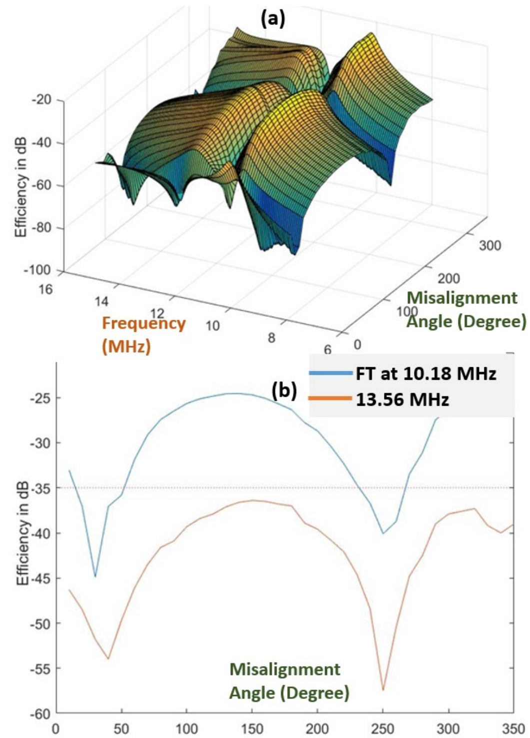

Fig. 5. (a) Wet tank 3D graph. (**b**) Wet tank PTE for both resonant frequency and tuned frequency (FT).

Acknowledgment

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References

[1] F. Brette, G. Luxan, C. Cros, H. Dixey, C. Wilson, and H. A. Shiels, "Characterization of isolated ventricular myocytes from adult zebrafish (Danio rerio)," *Biochemical and Biophysical Research Communications*, vol. 374, pp. 143-146, 2008.

[2] Y. Shiba, S. Fernandes, W.-Z. Zhu, D. Filice, V. Muskheli, J. Kim, et al., "Human ES-cell-derived cardiomyocytes electrically couple and suppress arrhythmias in injured hearts," *Nature*, vol. 489, pp. 322-325, 2012.

[3] H. Cao, F. Yu, Y. Zhao, X. Zhang, J. Tai, J. Lee, et al., "Wearable multi-channel microelectrode membranes for elucidating electrophysiological phenotypes of injured myocardium," *Integrative Biology*, vol. 6, pp. 789-795, 2014.

[4] A. B. Amar, A. B. Kouki, and H. Cao, "Power approaches for implantable medical devices," *Sensors*, vol. 15, pp. 28889-28914, 2015.

[5] H. Cao, V. Landge, U. Tata, Y.-S. Seo, S. Rao, S.-J. Tang, et al., "An implantable, batteryless, and wireless capsule with integrated impedance and pH sensors for gastroesophageal reflux monitoring," *Biomedical Engineering, IEEE Transactions on*, vol. 59, pp. 3131-3139, 2012.

[6] A. P. Sample, D. T. Meyer, and J. R. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 544-554, 2011.