A Novel Design to Power the micro-ECG Sensor Implanted in Adult Zebrafish

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***Abstract*—Heart diseases have been the leading cause of death in the developed world, partially due to failure to adequately replace lost ventricular myocardium from ischemia-induced infarct. Adult mammalian ventricular cardiomyocytes have a limited capacity to divide, and this proliferation is insufficient to overcome the significant loss of myocardium from ventricular injury. Unlike mammalian hearts, zebrafish (*Danio rerio*) hearts fully regenerate after 20% ventricular amputation in 2 months, thereby providing a genetically tractable model system for heart regeneration investigations. Recently, electrocardiogram (ECG) assessment in zebrafish has showed promise as an alternative method to study heart regeneration and heart diseases; however, all existing approaches involving the use of anesthesia drugs are inadequate to provide intrinsic ECG signals. Towards a wireless ECG platform, we use the wireless power transfer (WPT) technique via inductive coupling to power an ECG sensor implanted in an adult zebrafish. The transmitter coil is a solenoid wound around a customized cylindrical housing while the compact receiver solenoid on the fish is modified to counter misalignment issues. The ECG data are sent to the external unit via backscattering in the form of load modulation using the same inductive link. Our system enables continuous monitoring of freely-swimming fish without disrupting their normal activities. An adaptive tuning method is used and power transfer efficiency (PTE) is characterized using a vector network analyzer (VNA) via S-parameter measurement.**

Keywords—zebrafish; ECG; heart regeneration; inductive coupling; wireless power transfer.

I. INTRODUCTION

The zebrafish (*Dario rerio*) model has become increasingly important as a biological resource, because of its small size, short generation time, easy manipulation of embryos and optical transparency, as well as numerous accessible mutants. It has been used to study aspects of gene functions that can be directly related to human diseases. For instance, unlike humans, zebrafish hearts can fully regenerate following cardiac injury, thereby providing a tractable model system to study endogenous heart regeneration. Zebrafish has also been proven to be an ideal vertebrate model system for phenotype-based screening. Owing to their physiological similarity to mammals, this forward genetic approach in fish opens a rapid avenue to reveal the genetic basis and underlying molecular mechanisms of numerous heart diseases [1, 2].

Conventionally, the adult zebrafish heart were assessed using optical and immunohistochemical methods, as well as system biology or molecular biology approaches, to study the roles of various signaling pathways in cardiac development and regeneration at the cellular level. Although possessing obvious advantages, those invasive approaches fail in studying the progress of the process (i.e. regeneration and remodeling) of the same animal over time as studied objects have to be sacrificed for analyses. Further, they cannot indicate the overall functionalities of the myocardium under investigation. Recently, our laboratory and others have been using ECG assessment as a means to monitor the development, regeneration and remodeling of zebrafish hearts. We have demonstrated the acquisition of ECG in adult zebrafish using microelectrode array (MEA) membranes, providing favorable signal-to-noise ratio (SNR) with clearly-recognized features of P waves, QRS complexes and T waves [1]. The acquired ECG signals were distinguishable between heart-injured fish and shams; thus enabling a novel tool to investigate zebrafish hearts. However, the data acquisition required repeated ECG measurements with sedated animals, rendering the past work stressful to the fish and inadequate to provide intrinsic ECGs which are critical for biological investigations.

In this context, we developed a novel system using wireless power transfer (WPT) via inductive coupling to operate a compact ECG sensor based on a flexible membrane mounted on the fish body, such as the one described in [1], enabling continuous long-term ECG monitoring of freely-swimming fish. Our system consists of two parts, the transmitter and the receiver units. The transmitter unit has a solenoid (TX) wound around an in-house cylindrical fish housing, and electronics. The receiver unit includes the ECG sensor, the receiver coil (RX) and compact electronics. The use of solenoids helps minimize the misalignment issues which are critical to planar antennas [3]. ECG data communication is realized via load modulation. In this work, we implement a novel orthogonal RX solenoid in order to maintain a sufficient power received in the fish implant. The power transfer efficiency (PTE) of the overall system is optimized by a frequency tuning process reported previously [4] and compared between a straight solenoid and an orthogonal solenoid as the RX. The conceptual design of the entire system and the frequency tuning process are illustrated in **Fig. 1**.

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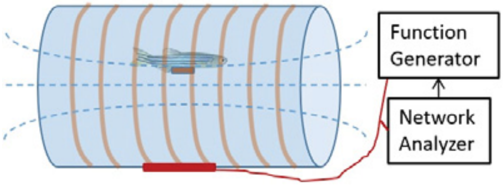

Fig. 1. Conceptual design with WPT and frequency tuning.

Measurements of PTE via a VNA provide feedback for frequency tuning.

II. Design and Implementation

The carrier frequency for power transmission should be in the range of 1 to 30 MHz to minimize absorption by the water. The class-E amplifier was chosen to power the TX owing to its reliability and efficiency.

The cylindrical housing is 32 cm long with a diameter of 8 cm. The TX has a dimension of Φ9 cm × 16 cm resulting in an inductance of 130 µH. The TX was designed to run the length of the tank to ensure a consistent magnetic flux throughout the system. The RX coil was a solenoid bent in the middle to obtain the orthogonal shape. It has an inductance of 1.5 µH. The TX and RX are showed in **Fig. 2**.

In this work, we apply the frequency tuning method recently report in [4] to maximize and stabilize the PTE. As the fish moves around the tank, the mutual coupling of the coils, k, would change, resulting in fluctuations of the received power. We used a directional coupler in the TX to identify the reflected power and minimized it by altering the operating frequency. Due to the swift movement of zebrafish, the coupling between the two coils fluctuates rapidly, thus ultimately a dedicated fast-response auto-tuning integrated module will be needed to ensure continuous monitoring of ECG.

III. Experiment and Results

Using the VNA, the resonant frequencies of TX and RX were tuned to approximately 1 MHz. The RX coil had an inductance of 1.5 µH, thus C_{ref} was adjusted to be 20 nF. The TX had a value of 130 µH, and its C_{ref} was adjusted to be 190.85 pF. First, we used a straight TX and carried out the experiment to measure PTE ($|S_{21}|^2$) as the TX and RX coils became misaligned. Power measurements were taken as the angular relativity between the coils was adjusted in increments of 10°. As the RX approached 90° to the TX, the PTE reached zero (**Fig. 3a**). Then, the frequency tuning was used to improve the coupling between the TX and RX coils. Continuous tuning of the transmission frequency enhanced the received power of the RX coil. However, when the relative orientation of TX and RX approached 90°, the PTE was slightly improved.

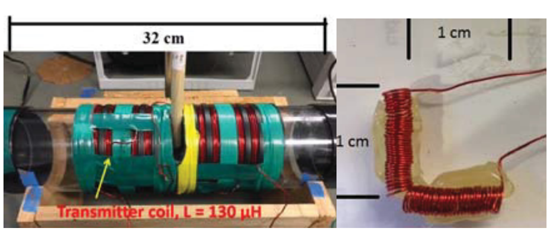

Fig. 2. TX tank and coil (left) and the orthogonal RX coil.

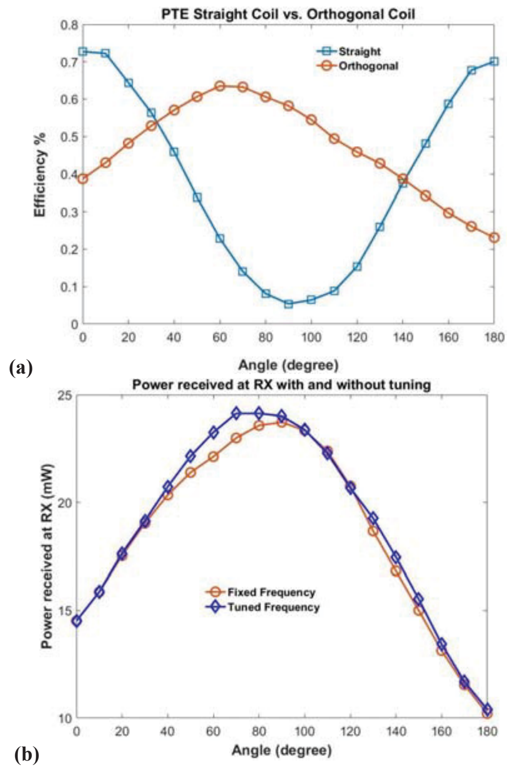

Fig. 3. (a) PTE comparison between the straight RX and the modified orthogonal RX. **(b)** Tuning results of the orthogonal RX solenoid.

Similar experiments were repeated with the orthogonal RX. As the modified RX can be seen as two orthogonal solenoids in series, the misalignment issue did not play a critical role (**Fig. 3a**). The PTE was further enhanced by the frequency tuning process. The results are showed in **Fig. 3b**.

IV. Conclusion

We have demonstrated a novel design of a WPT system to power an ECG sensor implanted in zebrafish, paving the way to numerous important heart-disease studies. Our approach also holds a promise to realize simultaneous monitoring of multiple fish, which would help save time and cost tremendously.

References

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