A Millimeter-Size Wirelessly Powered CMOS Data Transceiver for Real-Time Signal Acquisition and Closed-Loop Modulation of Human Brain Functions

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***Abstract*—Low power and energy harvesting sensors based on an integrated system-on-chip approach enable a broad range of application such as ubiquitous sensing and biomedical implants. In this report, we discuss motivation, system level architecture, and measured results of a wirelessly powered ultra-low power data transceiver that is compatible with footprint constraints and available power budget of biomedical implants. The system receives energy through an inductive near-field wireless link which also incorporates downlink data with an ASK modulation scheme. The proposed system adopts a frequency division duplexing scheme to minimize the effect of power transmission link on the uplink communication circuitry. We demonstrate a reconfigurable data transmitter that can communicate uplink data with either OOK or UWB modulation schemes.**

***Index Terms*— CMOS; FDD radio; implantable electronics; on-chip antenna; silicon; transceiver; ultra-low power; UWB; WPT.**

I. Introduction

Recent advances in integration and semiconductor technology have led to the development of new systems and devices that are capable of operating inside the human body. Miniaturization is one of the key requirements of Implantable Medical Devices (IMDs) since it is the solution for improving the spatio-temporal resolution of the recorded signals. Miniaturization leads to a higher sensor density and enables signal recording at an ultra-small structural scale. In addition, smaller implants cause less damage to the living tissues, ease up the encapsulation process, and are easier to be implanted [1]. Energy harvesting methods have shown to be a promising approach for powering small IMDs. Integrating the entire system, including the power harvesting module and antennas, in a standard CMOS die is an elegant solution for improving the reliability of the IMD and reducing overall cost, and form factor of the system. On the other hand, the IMD should be able to communicate information with a relatively high data-rate to enable real-time monitoring and decoding of human cognitive functions. Given the challenges that are imposed by wireless power delivery to a mm-sized IMD, data communication with a high rate is really challenging and requires a great amount of effort to design a low-power and efficient data transceiver. The objective of this project that is supported by IEEE MTT-S Graduate Fellowship for Medical Applications is to develop mm-sized IMDs for closed-loop neural recording and stimulation with a focus on power harvesting platform and low-power data transceiver.

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II. Guidelines For Manuscript Preparation

Delivering the maximum possible power is one of the most important goals in the design of an IMD since it determines the functionality of the system. Traditionally, wireless power transfer systems utilize a pair of cm-sized coils to transfer energy with low-MHz RF signals. [2], We demonstrated a mm-sized power harvesting system for high-performance biomedical implants such as neural recording devices. To tackle the challenges associated with power transfer through biological tissues, a multilayer planar model was presented, and the wireless link was optimized to achieve the maximum power transfer efficiency. Increasing the carrier frequency to sub-GHz or even GHz made it possible to shrink the size of receiving antenna and implement it on a silicon chip.

The challenges of wireless power transfer to miniaturized implants are discussed in detail in [2] and a dual-mode power harvesting system is proposed as the remedy to these problems. The main challenges can be listed as: 1- The small size of the Rx coil causes the power transfer efficiency to be lower compared with traditional systems 2- The available power is limited by safety regulations to ensure the specific absorption limits are met. 3- The nonlinear behavior of power conversion circuitry degrades the conversion efficiency and limits the available power budget. We presented a 1.6×1.6 mm^2 dual-mode wireless power harvesting platform with an on-chip coil for millimeter-sized biomedical implants. The system is fabricated in the 180-nm SOI CMOS process with a micrograph shown in Fig. 1(a). The design introduces a power management technique that makes the power harvesting system immune to the variations of wireless link efficiency that can be caused by tissue type variation, misalignment, and movement of Tx and Rx coils. Depending on the available RF power at the Rx and the power consumption of the load, the PMU sets the power delivery state to continuous or duty-cycled mode, which enables the system to drive implants with a wide range of power consumption. The block diagram of the design and the measured waveforms of the PMU are shown in Fig 1(b) and Fig. 2, respectively. Measurement results show that the designed system achieves a wireless link efficiency of 0.68%

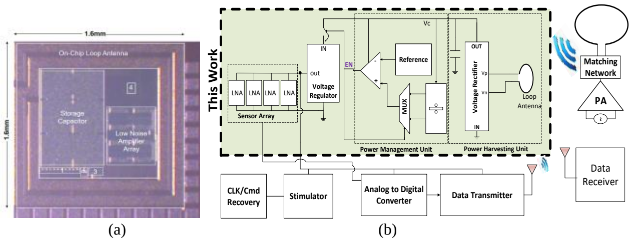

Fig. 1. (a) Chip micrograph of the power harvesting system and (b) Block diagram of the design.

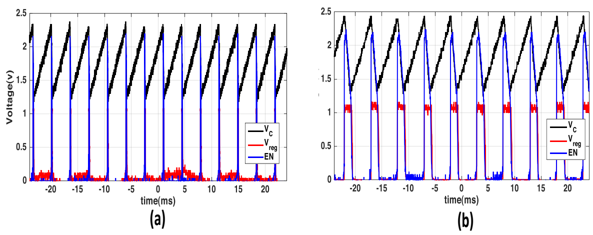

Fig. 2. PMU measured waveforms. P_T = 50 mW (a) regulator load is 1KΩ. (b) Regulator load is 8 KΩ.

and an FOM of 165.1. The fabricated chip adaptively sets the power delivery mode that is capable of delivering up to 1.17 mW in the duty-cycled mode while the amount of transmitted power is 15 dBm.

III. Wirelessly Powered Transceiver

Emerging applications of biomedical devices demand millimeter-scale implants with high-throughput wireless communication to support high-density recording/stimulation interfacing systems. Data communication is one of the most critical tasks that dominates the overall performance of an implant. Therefore, the research trend in medical applications is focused on wirelessly powered transceivers (TRX) with smaller form-factors and higher efficiencies. Active radios have been demonstrated with >10Mbps data-rate and >5cm operating range, recently. However, off-chip components that are used for power delivery and data communication have limited integration capability of these devices and there is a significant need for developing an integrated TRX with a mm-sized form-factor and satisfying DR.

We present an integrated wirelessly powered TRX with on-chip antennas and a total area of 2.4×2.2×0.3 mm^3 achieving 2.5 Mbps downlink (DL) DR with 1.04 pJ/s efficiency, maximum uplink (UL) DR of 150 Mbps under duty-cycled operation, and a maximum UL energy efficiency of 4.65 pJ/b [3]. The block diagram of this design is shown in Fig. 3. The chip is fabricated in TSMC 180nm CMOS technology and the micrograph is shown in Fig. 4. The robust operation is enabled by the following techniques: 1- Co-optimizing the on-chip coil (OCC) and the wireless link with voltage rectifier to maximize power transfer efficiency. 2- Combining MOSCAP (5.5 fF/μm^2) and MIM (2 fF/μm^2) capacitors to realize a ~5nF on-chip capacitor for energy storage. 3- Employing a power management unit (PMU) to set the operating mode and biasing condition of different blocks depending on the available power and power consumption of the system. 4- Utilizing a dual-antenna architecture to minimize the interference between power link and UL communication. 5- Exploiting amplitude-based

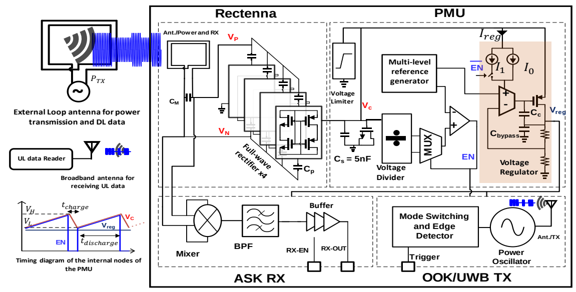

Fig. 3 Block diagram of the proposed configurable dual-antenna transceiver; and conceptual timing diagram of PMU waveforms during operation.

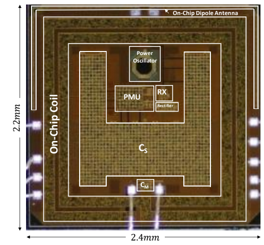

Fig 4. Die micrograph of the reported wirelessly powered dual-antenna transceiver.

modulation schemes in UL and DL for maximizing energy efficiency and utilizing an architecture based on a power oscillator (PO) in the transmitter (Tx) block to achieve the highest possible energy efficiency. Applying all these techniques, the proposed design can be powered remotely from an external loop antenna located ~1cm apart from the chip while the transmitted power level (P_{TX}) is limited to 25dBm. The TX block communicates UL data with either OOK or UWB modulation scheme to an antenna at 15cm distance [4].

IV. Fellowship Impact and Career Goals

I am planning to pursue an academic career with a focus of RF and microwave engineering for a variety of applications including bioelectronics, ubiquitous sensor network, and low-power integrated circuits. I am truly honored to be recognized as one of the top students in the field of microwave engineering and to receive the MTT-S Graduate Fellowship. I believe this fellowship has improved the quality of my research, boosted the visibility of my research, and expanded my professional network by through attending IMS 2019 conference. I am deeply thankful to MTT-S society and I look forward to engaging in future IEEE MTT-S efforts for promoting the area of microwave engineering.

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