

The Development of a RFID Based Mixed Signal ASIC for the Wireless Measurement of Intraocular Pressure

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Abstract— The initial development of a wireless transponder for an IOP monitor capable of performing uninterrupted measurement for 24 hours a day is presented. This work eliminates the need for a permanent power and data link between an external reader and the ophthalmic implant, thereby greatly reducing the required patient interaction. The transponder consists of a custom developed Application Specific Integrated Circuit (ASIC), pressure sensor, FRAM memory, and a super capacitor based power module. The ASIC was fabricated using a 0.5- μm CMOS process and implements a RFID-based inductively coupled front-end operating at 13.56 MHz. The data logging circuit is designed to sample pressure once every 10 minutes. Power consumption of the transponder operating at $V_{DD}=2.8\text{ V}$ and $F_{CLK}=140\text{ kHz}$ is estimated at 30 μA during data logging read/write phases and 12 μA for timing operations.

Keywords- RFID; IOP; glaucoma; pressure implant.

I. INTRODUCTION

Glaucoma is the leading cause of preventable blindness in the U.S. and is treated by the reduction of intraocular pressure (IOP) within the eye [1]. IOP is measured by two methods: tonometry and manometry [2]. Tonometric means of IOP measurement are limited by their ability to only provide discontinuous pressure readings [3]. Although continuous, orbital manometry is a surgically invasive procedure requiring the creation of a fistula in the sclera and requires immobilization and anesthization of the eye. Researchers have sought to overcome these difficulties through the implantation of miniature pressure sensitive transponders within the eye [4]-[7].

Modern devices often utilize Radio Frequency Identification technologies (RFID) [8]-[10], because the small size and lack of batteries make RFID based platforms ideal. Power and pressure data are transmitted wirelessly, therefore after implantation nothing pierces or touches the globe. However, traditional passive RFID architectures of bio-telemetric chips are limited in functionality, as they require close proximity to the RFID reader for continuous monitoring, do not contain writeable memory circuits, and are not capable of storing charge. The techniques utilized to address the close proximity requirement [8] have limited the medical

implementation of inductively coupled RFID tags that are otherwise well suited for IOP monitoring.

The present work was undertaken to develop a RFID transponder capable of monitoring IOP without the need for a permanent power and data link. This was accomplished via the creation of transponder that includes a custom ASIC containing a digital controller capable of data logging operation, as well as the wireless telemetry interface found in standard RFID transponders. The digital controller autonomously interfaces a MEMS pressure sensor and a FRAM IC to read and store pressure data locally using the Serial Peripheral Interface (SPI) bus. The transponder presented is capable of autonomously sampling IOP once every 10 minutes over a 24-hour period. The transponder must only be interfaced with a reader once daily to retrieve data and to recharge the device for the next 24-hour operation cycle.

II. PRINCIPLE OF OPERATION

Intraocular pressure is measured by the implantation of an RFID transponder/data logger within the eye (Fig. 1). The transponder utilizes a commercially available sensor consisting of a capacitive sensing element and signal conditioning /interface Integrated Circuit (IC), which is configured to operate as a slave device. The ASIC, operating as a master controller, initiates pressure readings at ten-minute

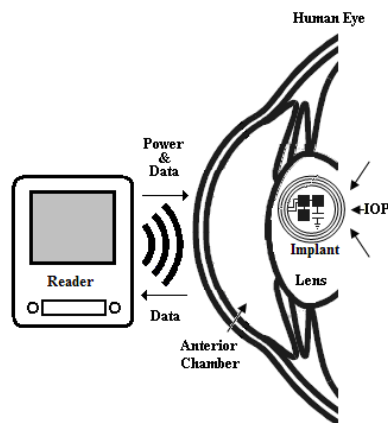


Figure 1. Implant transponder within the eye interfaced by an external RFID reader.

intervals, downloads data from the sensor IC and interfaces a FRAM device to store data. The pressure sensor and FRAM are powered-down when not in use to reduce system power consumption. The pressure data stored in memory can be wirelessly retrieved at any time through operation of the transponder ASIC as a passive RFID interface, with communication initiated by the reader. The downlink data is formatted according to a custom protocol based on the existing SPI standard [11], which we call Wireless SPI. Data transmission from the transponder to the reader is achieved via the technique of load modulation, which varies the impedance of the LC tank in the transponder in time with digital data. The pressure sensor IC and FRAM IC can both be individually serially addressed by the RFID reader using the Wireless SPI protocol.

III. TRANSPONDER ARCHITECTURE

Fig. 2 is a block diagram of the component connections of the implant transponder: antenna, ASIC, tuning capacitors, pressure sensor, FRAM, and power supply capacitor. The antenna, in parallel with tuning capacitor C1, forms a parallel LC circuit tuned to 13.56 MHz. This is used to receive both power and data, which are recovered from a RF carrier wave generated by a remote reader. The ASIC contains voltage rectification and regulation circuitry to supply power to the transponder and to charge the super capacitor, Cp. Also, the ASIC contains an envelope detector to demodulate the transmitted ASK downlink data (utilizing capacitor C2). A CMOS digital interface was developed to demodulate the downlink data, interface with the pressure sensor and the FRAM via the SPI protocol. It also generates Manchester encoded (ME) digital data for uplink communications, and controls the microsystem during autonomous operation. Uplink data is transmitted from the microsystem to the reader by switching a modulation FET (modFET) in time with data to varying the load impedance reflected to the reader antenna from the tag antenna. This technique is also known as inductively coupled load modulation. The pressure sensor contains a capacitive sensing element, circuitry for signal conditioning and digitization of pressure data, and SPI interface circuitry. The FRAM is used to store digital data (pressure, patient, calibration, etc.) and is also interfaced by the ASIC via the SPI protocol.

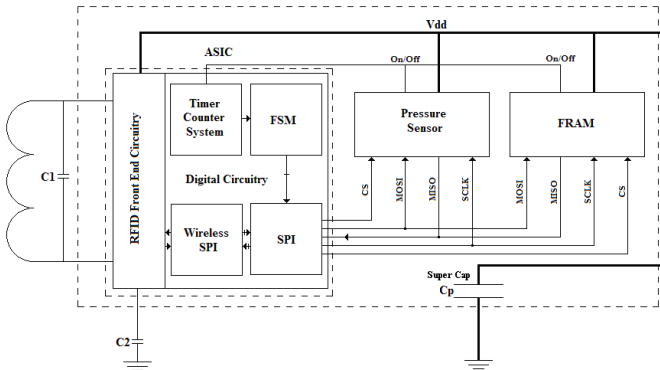


Figure 2. Block diagram of the pressure measurement and data storage transponder.

IV. SYSTEM OPERATION

The transponder operates in three modes: charging, wireless SPI, and data logging. The active mode of operation is determined by the properties of the voltage induced in the RFID front-end by EM coupling with the reader, and in turn a DC signal produced by the RFID front-end circuitry (Table 1). In each mode, different components of the microsystem are activated and deactivated as necessary. These modes are described in detail in the following sections.

A. Charging

In charging mode the unmodulated carrier wave is rectified and regulated to constant DC by the RFID front end circuitry. This constant DC supply is used to charge the super capacitor power supply.

B. Wireless SPI

In wireless SPI mode control of the transponder is handled by an RFID reader, and a single communication between the remote host reader and either peripheral device of the microsystem implant is termed a wireless SPI (WiSPI) communication frame. A WiSPI frame begins with the downlink transmission of Manchester encoded digital data via ASK modulation of the carrier wave and ends with the uplink transmission of digital message data from a peripheral via load modulation. A complete wireless SPI frame is illustrated in Fig. 3. Downlink WiSPI data is 27 bits in length and is transmitted big-endian. The 24-MSBs (26 down to 3) contain the appropriate op-code for a single SPI frame. The op-code must be formatted in accordance to the frame format specifications of the peripheral manufacturer. If an op-code is less than 24bits in length, the remaining bits should be filled with don't care values. SPI frames greater than 24-bits are not supported. Bit 2 is the Device Select Bit. A Device Select Bit of 0 selects the peripheral connected to CS1 and a Device Select Bit of 1 selects the peripheral connect to Cs2 of the transponder SPI bus. The 2 LSBs of the downlink data indicate the length of the actual SPI frame. (00=8-bits, 01=16, and 10=25 bits). Downlink data is appended to 7 additional bits before Manchester encoding to aid in synchronization with the microsystem RFID front-end. The RFID front-end of the

TABLE I. OPERATIONAL MODES OF THE TRANSPONDER.

MODE	EM COUPLING TYPE (RFID Front-End Voltage)	ACTIVE COMPONENTS
1. Charging	Non-modulated carrier wave (Constant DC w/o strobe output)	Antenna, RFID Front End, Super Cap Power Supply
2. Wireless SPI	100% ASK modulated carrier wave downlink, load modulation uplink (Constant DC w/ strobe output)	Antenna, RFID Front End, Wireless SPI, SPI, Sensor, FRAM
3. Data Logging	No EM coupling (0V DC)	Timer/Counter, Data Logging FSM, SPI, Sensor, FRAM, Super Cap

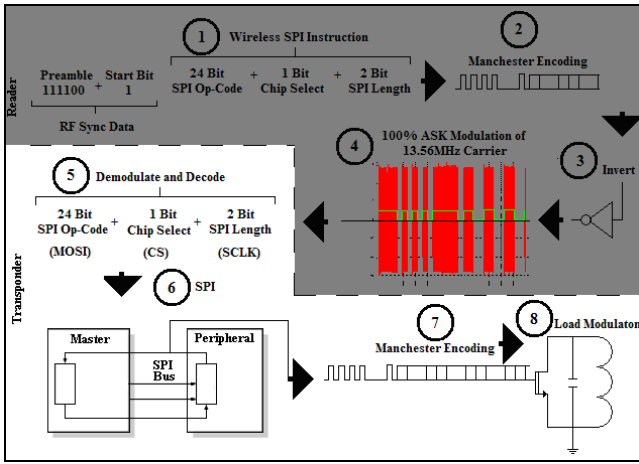


Figure 3. RFID reader and transponder communication via Wireless SPI.

ASIC contains a demodulating circuit for the retrieval of the ME WiSPI data. The demodulated ME data is then converted to NRZ binary by a 16x over-sample Manchester Decoder. The Manchester decoding circuit passes NRZ data to a parsing module which separates the op-code message from the chip-select and the data length bits, and transfers them to the SPI Master. The SPI master then initiates a single wired SPI frame. MISO data is stored in a 24-bit shift register internal to the SPI master, and is clocked in on SCLK. If an SPI transmission is less than 24-bits, the unused LSBs of the shift register default to 0s. Once a wired SPI frame is complete, a Manchester encoding circuit reads the 24-bit SPI MISO shift register contents, adds a preamble and start bit, Manchester encodes the, and modulates a nmos FET connected in parallel with the tuned antenna.

C. Data Logging

In data logging mode control of the transponder is handled by the ASIC. A timer/counter monitors clock transitions of an on-chip oscillator. On ten minute intervals, the timer initiates a digital finite state machine (FSM) and powers on the pressure sensor and FRAM via a power gating circuit. The FSM iteratively loads hard-coded SPI commands into an SPI master module. The SPI Master initiates a SPI communication frame for each state of the state machine to acquire pressure data and store the data to memory. Once a pressure reading has been recorded, the ASIC disables the SPI peripherals and issues a reset to the digital logic

V. ASIC DESIGN AND FABRICATION

The CMOS ASIC was designed using a combination of digital standard cells and custom analog cells. The digital architecture was developed using VHDL and RTL simulation software, and was mapped to the 0.5 micron standard cell digital library, and auto-place-and-route was performed with a layout editor. The analog architecture was manually designed and routed in a layout editor. The ASIC was fabricated in the On Semiconductor 0.5 micron CMOS process through MOSIS. Fig. 4 illustrates the final IC, consisting of one fully integrated tag along with an additional discrete FSM, all within a 100-pad frame. The frame provides VDD and

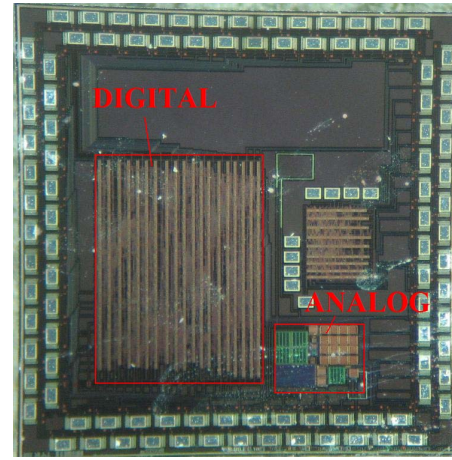


Figure 4. Transponder ASIC (3.3mm x 3.3mm) photograph showing RFID front-end and digital control/interface logic.

GND bus connections, as well as integrated ESD protection circuits. The final die size was 3.3 mm x 3.3 mm. The ASIC was packaged in a 120-pin PGA for testing purposes.

VI. TESTING AND RESULTS

The packaged ASIC was interfaced with the SPI peripherals via a custom bread-board interface. The transponder was tested in both data logging mode and wireless SPI mode. During data logging mode tests, power to the transponder was provided with a power supply operating at 2.7V DC. During wireless SPI mode, power to the transponder was provided via an Agilent 33250A function generator generating a 3V peak to peak 13.56 MHz wave. Downlink digital data was simulated with the use of a Xilinx Spartan3 FPGA. In both modes, SPI bus traffic was monitored with an Agilent MS06104A mixed signal oscilloscope to verify functionality.

The digital circuit functions as designed in both wireless SPI and data logging modes with two exceptions. An incorrectly defined tri-state inverter cell was utilized as the output buffer on the MOSI line of the SPI Master. Use of the cell caused the MOSI output to enter a high-Z state, as depicted in Fig. 5. This resulted in an inability to send SPI commands to either the pressure sensor or the FRAM. Additionally, a manual layout error resulted in a failure to connect the output of the RFID front-end demodulator to the digital Manchester decoder. This resulted in an inability to transmit downlink data via the RFID front end, but a by-pass of this input was included on the ASIC

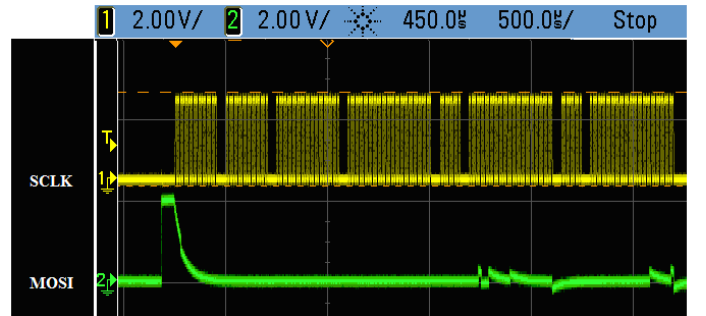


Figure 5. MOSI output behavior with high Z inverter as buffer.

for testing purposes. Operation of the RFID front end was therefore validated by verification of the voltage rectification and regulation of the 13.56 MHz carrier, as depicted in Fig. 7. A circuit redesign has addressed these defects of the ASIC and has been implemented in a second generation ASIC currently in fabrication.

Current consumption of the IC operating at VDD=2.8 V and FCLK=140 kHz was measured to be only 12 μ A. Additionally, when interfaced by the ASIC the pressure sensor draws 3.5 μ A, and the FRAM draws 15 μ A. For operation over a 24-hour period, the transponder requires ~1.04 C of charge, and is dominated by the continuous current draw of the ASIC. Operation of the transponder over the course of a day therefore requires a 3.46 F capacitor with a supply range of 2.8V down to 2.5V. By extending power gating techniques to the digital logic of the transponder ASIC, it is estimated that transponder current draw can be reduced to ~1 μ A in between data logging cycles. Such an implementation would reduce the required super capacitor supply to only .28 F for 24-hours of operation (Table 2). Such capacitors are available in 6.8 mm x 1.8 mm form factors that are within the dimensional restrictions of the transponder design. Additionally, the transponder draws an estimated 30.5 μ A during wireless SPI mode which must be sourced by the RFID reader.

VII. CONCLUSION

We have presented the first design of a dual mode RFID transponder for telemetry via wireless SPI, and autonomous data logging. The data logging function is utilized to collect and store IOP in the eyes of glaucoma patients. The wireless telemetry function allows for the interrogation of the transponder by a remote reader to retrieve stored data and to perform calibration and patient identification functions. Additionally, the RFID implements a unique communication protocol, Wireless SPI, to address SPI enabled peripherals. Such a device could find a wide variety of applications in such fields as bio-telemetry, environmental monitoring, and distributed sensor networks.

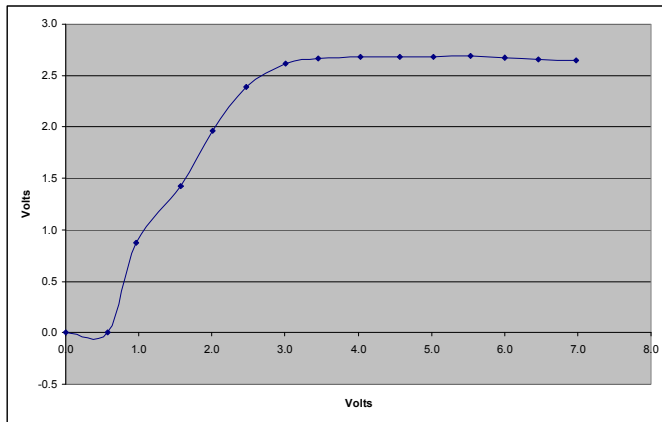


Figure 6. DC output voltage of RFID front-end as a function of input voltage.

TABLE II. SUPER CAPACITOR CHARGE REQUIREMENT CALCULATIONS

ASIC w/o Standby				
Device	Current (A)	On Time (s)	Charge(C)	Cap. (F)
ASIC	1.20E-05	86400	1.04	
FRAM	1.50E-05	0.4608	6.91E-6	
Sensor	3.50E-06	0.2304	8.06E-7	
Total			1.04	3.456
ASIC w/ Standby				
Device	Current (A)	On Time (s)	Charge (C)	Cap. (F)
ASIC	1.20E-05	0.6912	8.29E-6	
ASIC Standby	1.00E-06	86399.3088	8.64E-2	
FRAM	1.50E-05	0.4608	6.91E-6	
Sensor	3.50E-06	0.2304	8.06E-7	
Total			8.64E-2	0.288

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