Radio Frequency Front-End Circuitry for an Implantable Multiple Frequency Coil

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Introduction: Signal-to-noise ratio (SNR) of nuclear magnetic resonance (NMR) imaging and spectroscopy of implanted bio-artificial tissue constructs can be improved by placing a NMR receiver coil around the implanted construct and receive the NMR signal response through inductive coupling with the external surface coil [1]. The limitation of this approach is that the implanted coil cannot be directly tuned to multiple frequencies. To overcome this limitation, integration of the implantable receiver coil with a digitally-controlled capacitor [2] can be used to form a selective-resonant circuit capable of providing increased signal sensitivity at multiple NMR frequencies associated with important metabolic nuclei. Practical implementation of a fully implantable system requires system miniaturization and the capability of wirelessly controlling the digitally-controlled capacitance value.

We propose an integrated chip, fabricated in CMOS technology, which is designed for use as the RF front-end for a finite state machine to provide wireless tuning of the implanted receiver coil resonant frequency through the setting of digitally-controlled capacitor values. The RF front-end is capable of extracting clock and data waveforms from RF pulses transmitted through the external surface coil using a modulation scheme that is compatible with current NMR console technology. Fig. 1a shows the system block diagram, which consists of the integrated RF front-end circuitry, a voltage regulator, an integrated digitally-controlled capacitor array, and a serial-to-parallel finite state machine (FSM). This work describes the design and implementation of the integrated RF broadband receiver circuit for recovering data that will be used to wirelessly control the digitally-controlled capacitor array, thus providing the capability to wirelessly tune the implanted coil's resonant frequency.

Methods: The digitally-controlled capacitor array is capable of tuning a 20 nH implantable coil, using a 10-bit control word, to the NMR resonant frequencies of 190 MHz (^{31}P), 442 MHz (^{19}F), and 470 MHz (^{1}H) in an 11.1 Tesla environment. Improvements on the previous design [2] were implemented using a different capacitive structure resulting in reduced parasitic capacitance as well as multiple contact pads for reduction in added inductance resulting from bond wires, thus increasing the overall frequency range. The RF front-end consists of an envelope detector and clock and data recovery (CDR) circuitry that is capable of extracting data at a rate of 20 kbits/second from RF pulses with carrier frequencies over the range of 100 – 500 MHz. The RF receiver can detect transmissions through a secondary coil, or through the NMR receiver coil using a high impedance buffer, so as not to affect the implanted coil resonance with the capacitor array. The system is powered by a battery which is regulated by an off-chip linear regulator.

The CDR circuit was designed for use with a pulse-position modulation (PPM) scheme (Fig. 1b), where a combination of 3 RF pulses represents a single bit and the position of the middle pulse (20% or 80% duty cycle) determines the value of a 1 or 0. The received signal passes through a 4-stage RF multiplier and low pass filtering circuit (Fig. 1c) for stepping up the voltage level of the received signal and removing the high frequency carrier component for envelope detection. The resulting envelope is passed through a toggle flip-flop register for conversion to a pulse-width modulated (PWM) signal to be used as the clock for internal and external synchronous circuits. An integrator and latched comparator are used to discriminate between the short and long pulses of the PWM clock signal, where the full-rate (non-return-to-zero) data is extracted based on the charging of a capacitor during the active part of the period. The voltage (V_p) stored on the capacitor at the end of each period is compared to an on-chip reference voltage for determining the period's duty cycle, thus determining the corresponding data value. The recovered data is then passed through a differential decoder circuit, allowing for data recovery in the event of the receiver missing a RF pulse.

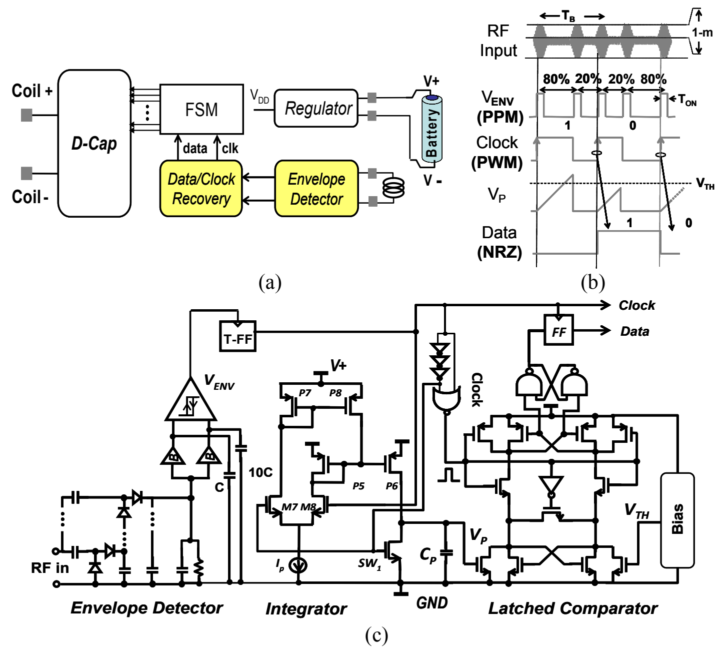

Figure 1. (a) System Block Diagram (b) Clock and Data Waveform Diagram and (c) RF Receiver Schematic.

Results: The circuit was fabricated using a 1.2 V, 130 nm CMOS process along with an improved capacitor array design. The die photo is shown in Figure 1a, with a core area measuring 650 µm x 450 µm and a measured power dissipation of 9 µW. Encoded data was wirelessly transmitted at a rate of 20 kbits/second using a transmit surface coil tuned and matched to 470 MHz. Figure 2b shows the recovered clock and data signals, measured on-chip using active high impedance probes. The capacitor array was connected to a 20 nH single turn, 12 mm diameter, copper receiver coil and loosely coupled to a broadband probe. The capacitance was electronically switched with a FSM and external clock and data to achieve the unloaded resonances at 190 MHz, 442 MHz, and 470 MHz shown in Fig. 2c.

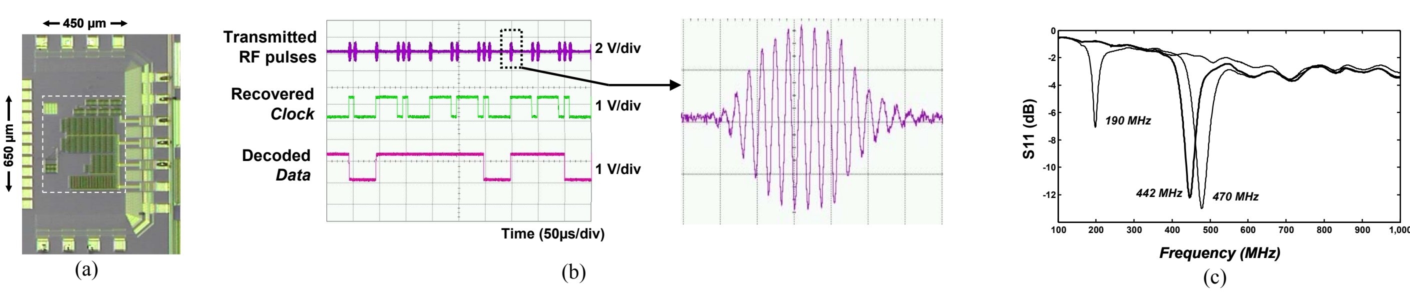

Figure. 2 (a) Die photo, (b) Wirelessly transmitted RF pulses and recovered on-chip clock and data, (c) Resonance measurements using external clock and data

Conclusion: These results demonstrate that the RF front-end is capable of recovering clock and data on-chip from transmitted RF pulses when coupled to an external surface coil. With a measured power dissipation of 9 µW, the system can be projected to last over 3 months using an appropriately sized 26 mAH primary coin cell battery. Further work can be done to allow for complete wireless control of the implantable coil's resonant frequency and make the system fully compatible with in vivo operation.

References: [1] Volland NA, *et al.*, "Development of an inductively-coupled MR coil system for imaging and spectroscopic analysis of an implantable bioartificial construct at 11.1T", MRM, in press [2] Turner W, *et al.*, ISMRM 2010, #424.
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