A 350μW CMOS MSK Transmitter and 400μW OOK Super-Regenerative Receiver for Medical Implant Communications

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Abstract

A 350μW MSK direct modulation transmitter and a 400μW OOK super-regenerative receiver (SRR) are implemented in 90nm CMOS technology. The transceiver tunes 24MHz in frequency steps smaller than 2kHz and is designed to meet the specifications of the Medical Implant Communications Service (MICS) standard in the 402–405MHz band. The transmitter meets MICS mask specifications with data rates up to 120kbps, and the receiver has a sensitivity better than –99dBm with a data rate of 40kbps or –93dBm with a data rate of 120kbps.

Introduction

In 1999, the FCC allocated the frequency band of 402–405MHz to the MICS standard for short-range ($\sim$2m) data communications with implanted medical devices [1]. The band is divided into ten 300kHz channels, and a maximum of 25μW of effective isotropic radiation power (EIRP) can be transmitted over each. Frequency stability must be within 100ppm ($\sim$40kHz) over the temperature range of 25–45°C. In this work, we maximally exploit the low output power and modest temperature stability requirements to reduce overall power consumption. The resulting power dissipation is over an order of magnitude lower than commercially available units [2].

The critical insight behind our transceiver architecture is that temperature regulation in the human body naturally reduces oscillator frequency drift. This allows us to replace the frequency synthesizer with a distributed feedback loop between the base-station and the implant. The base-station periodically measures DCO frequency drift and sends correction data to the implant. By eliminating the crystal oscillator (XO), the power, volume, cost, and system startup time are reduced, allowing more efficient duty cycling since XOs generally take milliseconds to stabilize.

The transmitter and receiver (Fig. 1) center around a differential Colpitts digitally-controlled oscillator (DCO) with a switching current source [3](Fig. 2). We exploit the low output power requirement of the MICS standard by incorporating a PCB loop antenna as the inductive element in the DCO's resonant tank. The antenna's high Q results in better noise performance, and its power dissipation is not simply wasted as thermal loss, but radiated to transmit information.

FSK data is transmitted by directly modulating the DCO with digital data, and a SRR architecture is used to achieve excellent sensitivity with minimal power consumption and allow a direct connection between the antenna and the oscillator. The DCO can tune within 1kHz ($\sim$2.5ppm) of a desired frequency over the range of 391–415MHz by sub-ranging the total capacitance through combinations of series and parallel capacitors. Thermometer-coded capacitor banks are used for coarse, medium, and fine tuning to ensure monotonicity and allow for predistortion leading to better linearity in digital-to-frequency conversion and over 13 effective bits of digital tuning.

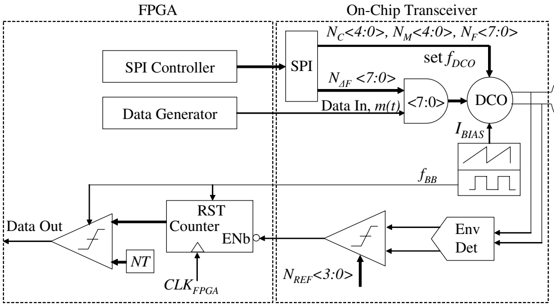

Fig. 1. Transceiver block diagram.

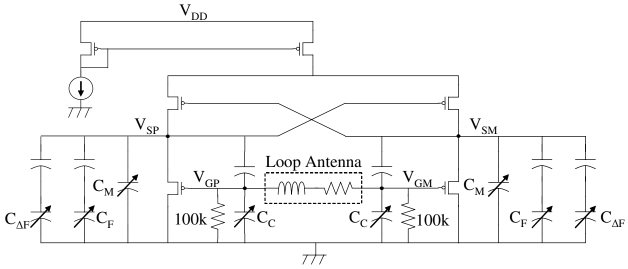

Fig. 2. Differential Colpitts digitally-controlled oscillator.

FSK/MSK Transmitter

FSK data is transmitted by directly modulating the DCO with digital data. The carrier frequency (f_C) and frequency deviation constant (ΔF) are digitally adjusted using capacitor banks C_C, C_M, C_F (coarse, medium, and fine tuning), and $C_{\Delta F}$. These capacitor banks are thermometer coded and predistorted to improve linearity in digital-to-frequency conversion. $N_{\Delta F}$, the digital word that controls $C_{\Delta F}$, is adjusted to generate the desired frequency shift to within 1kHz ($2\Delta F = 0.5 \times$Bit Rate for MSK). Each bit of $N_{\Delta F}$ is then applied to one input of an *and* gate, and the modulation data $m(t) \in [0, 1]$ is applied to the other input such that the DCO instantaneous frequency is $f_{DCO}(t) = f_C \pm 2\Delta F \times (m(t) - 0.5) \in [f_C \pm \Delta F]$.

Super-Regenerative Receiver

To receive OOK data, the DCO is used as part of a SRR. At the start of each bit period, the DCO tank is briefly shorted with an NMOS switch to extinguish all oscillations. The bias current is then linearly varied through an on-chip sawtooth oscillator from a value below I$_{crit}$ (the minimum current required for oscillation) to a value above I$_{crit}$. As the bias current crosses I$_{crit}$, the SRR effectively samples the input current

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[4] induced by the loop antenna and the DCO begins to oscillate. Larger input signals with strong frequency contents near the tank's resonant frequency lead to shorter startup times. As the oscillation grows, a fully differential envelope detector tracks the amplitude of the DCO, and a comparator switches states when the envelope rises above a programmable reference value (Fig. 3). A counter implemented on an FPGA begins counting at the start of the bit period and stops when the comparator output switches states. The count value, a measure of the DCO startup time, is compared to a threshold value to determine the data value received. Since the received signal is OOK modulated, a low/high count respectively corresponds to a received one/zero.

Measurement Results and Conclusion

The DCO consumes 500μA from a 0.7V supply and all other circuits consume less than 50μW combined. The total power consumption for the transmitter and receiver are 350μW and 400μW respectively, more than an order of magnitude lower than commercially available MICS transceivers. The transmitter meets the MICS mask specifications with 5dB of margin at a data rate of 120kbps (Fig. 4). Fig. 5 shows the linear and monotonic tuning characteristics of the DCO. A frequency drift of about 1MHz occurs over the 20°C temperature range ($\sim$125ppm/°C), which can be easily corrected with the proposed distributed feedback loop. Fig. 6 shows measured time domain signals at different points in the receiver chain. Receiver sensitivity is better than –99dBm for a data rate of 40kbps and –93dBm for a data rate of 120kbps (BER=10^{-3}). DCO phase noise is –108dBc/Hz at a 100kHz offset.

In conclusion, we present an ultra-low power transceiver optimized for medical implants. We reduce system level power by exploiting temperature regulation in the human body to replace frequency synthesis with distributed frequency correction. We reduce implant complexity and power by using a direct modulation transmitter and a super-regenerative receiver. We reduce circuit level power by incorporating a high Q PCB loop antenna into the DCO resonant tank, and we achieve 13 bits of linear frequency tuning by using predistorted capacitor banks.

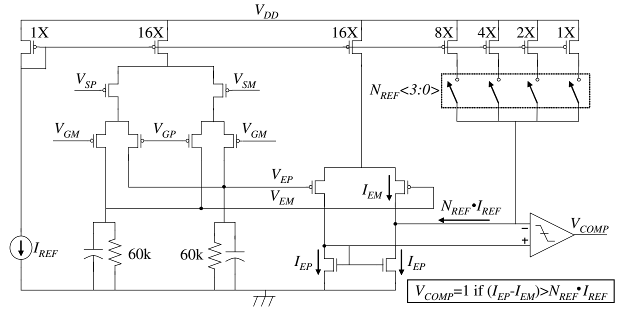

Fig. 3. Schematic for differential envelope detector and comparator with programmable reference.

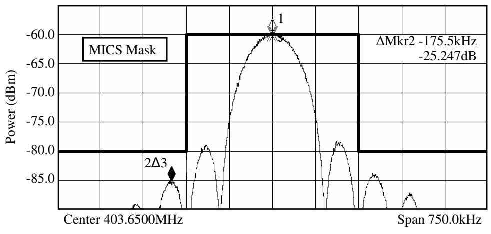

Fig. 4. Spectral mask of transmitter with 120kbps data rate. The plot is taken from an antenna 10cm from the tansceiver.

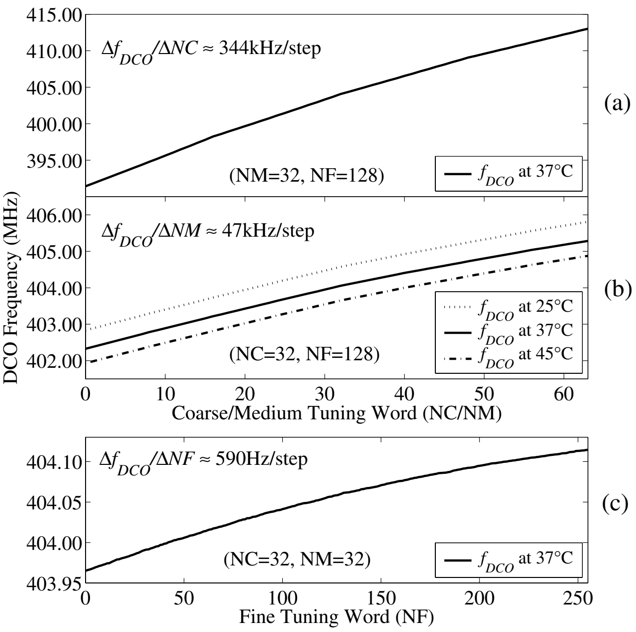

Fig. 5. DCO frequency for (a) coarse,(b) medium, and (c) fine tuning. Thermometer coding and predistortion of the capacitor bank leads to monotonic, linear tuning.

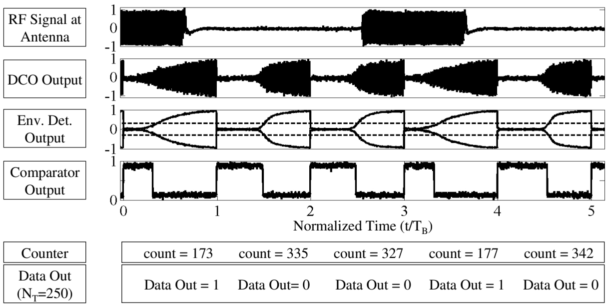

Fig. 6. Normalized time domain signals in the receiver chain.

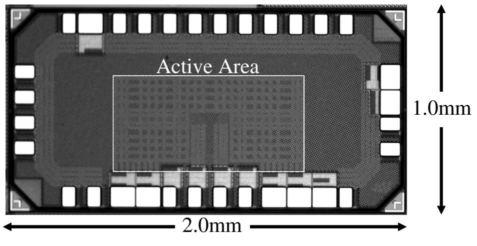

Fig. 7. Die photograph (1.0 x 0.5mm active area).

References

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