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A Pulsed UWB Receiver SoC for Insect Motion Control

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For decades, scientists and engineers have been fascinated by cybernetic organisms, or cyborgs, that fuse artificial and natural systems. Cyborgs enable harnessing biological systems that have been honed by evolutionary forces over millennia to achieve astounding feats. Male moths can detect a single pheromone molecule, a sensitivity of roughly 10²⁹ grams. Thus, cyborgs can perform tasks at scales and efficiencies that would ordinarily seem incomprehensible. Semiconductors are central to realizing this vision offering powerful processing and communication capabilities, as well as low weight, small size, and deterministic control. An emerging cyborg application is moth flight control, where electronics and MEMS devices are placed on and within a moth to control flight direction. To receive commands on the moth, a lightweight, low-power, and low-volume RX is required. This paper presents a pulsed ultrawideband (UWB) RX SoC designed for the stringent weight, volume and power constraints of the cyborg moth system.

A high-level drawing of the cyborg moth system is presented in Fig. 11.3.1. Commands are sent from a base station and received wirelessly on a Manduca sexta hawkmoth. A unidirectional wireless link is employed to reduce power consumption of the moth electronics. A 4-stage electrotonus stimulator is implanted in an adult moth to stimulate nervous tissue in the abdominal nerve cord, thereby causing abdominal movement, which has been shown to alter flight direction [1]. A 35nA, 0.2g Zinc-Air hearing aid battery supplies energy to the system at 1.3V, and is regulated to 1V and 2.5V by an LDO and a dc-dc boost converter. As the carrying capacity of a moth is limited to approximately 0.8g [2], a highly integrated UWB RX SoC is required. Pulsed UWB wireless signaling is employed as UWB radios can achieve highly integrated, energy efficient operation in nanometer CMOS processes.

A block diagram of the RX architecture and packet structure is shown in Fig. 11.3.2. The non-coherent, energy detection RX receives UWB pulses in one of three 500 MHz channels at 3.5, 4.0 and 4.5 GHz. The RX achieves near compliance with 802.15.4a but with minor changes to reduce power consumption. The received signal is amplified by an LNA and multi-stage frequency tunable RF amplifier and then squared to baseband. At baseband, the signal is amplified and then integrated in a 31.2ns window and converted to a 5-bit digital signal. The static performance of the 5-bit integrator and ADC is shown in Fig. 11.3.4. A high-speed, low-power, and low-volume RX SoC is required for low-power wireless transmission.

Following the LNA are 5 stages of tuned, differential inverter-based RF amplifiers. To achieve gain scalability up to 35dB, a programmable number of amplifiers can be enabled at any time. To dc bias each inverter, the center tap of each stage’s inductor is connected to the center tap of adjacent stages. As these nodes are virtual grounds this technique does not reduce gain. The inverter-based RF amplifier achieves comparable energy efficiency to low-voltage (0.5V) tuned amplifiers [4] while only requiring half the total number of inductors. Moreover, the higher operating voltage allows for a single core supply voltage of 1V while requiring significantly less current, easing power supply demands. Finally, the inverter-based RF amplifiers allow for simple implementation of a squarer with differential outputs.

The RX has been mounted on a miniature, 1.2cm by 2.5cm PCB and has successfully received packets on a moth while powered, inducing moth abdominal motion (Fig. 11.3.5). By changing the pulse frequency, the abdominal deflection can be varied between 0° and 7°. The PCB is attached to the moth’s dorsal thorax with glue and mounted like a fin. As the system weight is slightly more than the moth’s carrying capacity, the moth is not able to gain lift; however, when the moth is tethered from a string, normal wing movement and abdominal response to stimulation pulses is observed. In a separate experiment, mock PCBs have been mounted on a moth’s ventral abdomen using a harness and flight has been demonstrated with a 0.8g dummy load.

The RX SoC was fabricated in a 90nm CMOS process. The RX operates at a 16Mb/s instantaneous data rate and achieves a sensitivity of -76dBm at 10-6 BER, corresponding to a duty cycle sensitivity of -98dBm at 100kbs. The RX SoC instantaneous power scales from 8-to-22.7mW while demodulating data, yielding 0.5-to-1.4nJ/b. In the cyborg moth system, the duty cycled RX looks for a packet of data every millisecond, requiring an overall average system power of 2.5mW at 1.3V. A table of results is shown in Fig. 11.3.6. A die micrograph is shown in Fig. 11.3.7.

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References:
Cyborg moth motion control system. Figure 11.3.2: Block diagram of pulsed UWB RX SoC and packet structure.

Figure 11.3.3: Inverter-based, 6-stage RF front end. Any of the 5 stages following the LNA can be disabled to reduce power consumption.

Figure 11.3.5: Photo of tethered moth before and during stimulus, showing abdominal deflection, with stimulus measured results below.

Figure 11.3.6: Table of measured results.
Figure 11.3.7: Die micrograph of pulsed UWB RX SoC.