17.6 A Cubic-Millimeter Energy-Autonomous Wireless Intraocular Pressure Monitor

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Glaucoma is the leading cause of blindness, affecting 67 million people worldwide [1]. The disease damages the optic nerve due to elevated intraocular pressure (IOP) and can cause complete vision loss if untreated. IOP is commonly assessed using a single tonometric measurement, which provides a limited view since IOP fluctuates with circadian rhythms and physical activity. Continuous measurement can be achieved with an implanted monitor to improve treatment regiments, assess patient compliance to medication schedules, and prevent unnecessary vision loss. The most suitable implantation location is the anterior chamber of the eye, which is surgically accessible and out of the field of vision. The desired IOP monitor (IOPM) volume is limited to 1.5mm^3 (0.5×1.5×2mm^3) by the size of a self-healing incision, curvature of the cornea, and dilation of the pupil. Previously, a 5.4mm^3 (6×3×0.3mm^3) sensor was demonstrated with a 27mm antenna [2]. The antenna size allows the sensor to be recharged wirelessly but may complicate implantation procedures [3].

The aggressive IOPM size constraint creates major challenges for achieving high-resolution capacitance measurements, wireless communication, and multi-year device lifetime. Little energy can be stored on the tiny microsystem, calling for ultra-low power operation and energy harvesting. The required millimeter antennas or inductors result in lower received power and higher transmission frequency, both increasing microsystem power. We present a cubic-millimeter IOPM with energy-autonomous operation and wireless communication. The IOPM targets implantation with a minimally invasive procedure through a tiny incision that is routinely used for outpatient cataract surgery. Glass haptics are designed to anchor the IOPM using the natural elasticity of the iris, preventing tissue damage and allowing for simple removal. The IOPM harvests solar energy that enters the eye through the transparent cornea to achieve energy-autonomy. The microsystem contains an integrated solar cell, thin-film Li battery, MEMS capacitive sensor, and integrated circuits vertically assembled in a biocompatible glass housing (Fig. 17.6.1). The circuits include a wireless transceiver, capacitance to digital converter (CDC), DC-DC switched capacitor network (SCN), microcontroller (μP), and memory fabricated in 0.18μm CMOS.

The IOPM measures IOP every 15 minutes using a MEMS capacitive pressure sensor connected to a 7μW 3.6V CDC with through-glass interconnects (Fig. 17.6.2) [4]. The measurement interval represents continuous monitoring, does not need to be exact for medical diagnosis [3], and is controlled by a slow timer in the wakeup controller (WUC) [5]. The CDC generates an IOP-dependent current by dropping $V_{DD}/2$-V_{TH} (V_{REF}) across an impedance generated by switching the MEMS pressure sensor (C_{MEMS}) at 50kHz. Simultaneously, a larger fixed current is generated in the same manner with the same clock and fixed capacitors (C_1, C_2). Two capacitors with out-of-phase clocks are used to generate a more constant current source. This fixed current is mirrored and compared to the IOP-dependent current using $\Delta\Sigma$ modulation to digitize IOP. The IOP-dependent current is integrated by discharging capacitor C_{INT}. The voltage on C_{INT} (V_{INT}) is compared to V_{REF} with a clocked comparator. When V_{INT} drops below V_{REF}, the fixed current is also integrated onto C_{INT}, increasing V_{INT}. The CDC achieves a pressure resolution of 0.5mmHg, which exceeds the 1mmHg resolution of typical tonometric measurements, using a decimation filter that counts the output bitstream over 10k cycles (Fig. 17.6.3). Since the CDC measures the ratio of two currents, it has low sensitivity to V_{DD}, clock, and temperature variations. After the CDC measurement, IOP data are logged into the 4kb SRAM using the 90nW 0.4V 8b μP. The microsystem can store 3 days of raw IOP data. The μP can also perform DSP or compression on the IOP data to extend storage capacity to over 1 week.

The user downloads IOP data using an external device (ED), placed near the eye. The microsystem is designed to respond to a wireless query by coupling RF energy from the ED onto an LC tank, rectifying the AC signal, and generating a digital wakeup signal (U_0, U_1) with a variable offset comparator (Fig. 17.6.4). IOPM data are transmitted with an oscillator that acts as both a carrier generator and power amplifier (Fig. 17.6.4). The IOPM uses a dual-resonator tank to generate an FSK-modulated signal with two tones at 570MHz (f_0) and 690MHz (f_1). The large tone separation enables higher transmission distance by relaxing phase noise constraints. To transmit a *zero*, LC_1 is shorted by asserting D_1 and the oscillator runs at f_0 for 0.1μs using LC_0. A *one* is sent by oscillating at f_1 with LC_1. The signal is transmitted through the anterior chamber, 0.5mm cornea, and air [3]. The measured transmitter BER is 10^{-6} through 5mm of saline and 10cm of air (Fig. 17.6.5). This medium models the attenuation from aqueous humor in the eye and the distance from the eye to ED. The 4.7nJ/b 3.6V transmitter achieves a 4× improvement in energy efficiency over comparable work in highly-integrated biomedical implants [2][6]. The battery's peak current is 35 to 40μW, which cannot directly support wireless transmission. To prevent catastrophic V_{DD} droop, 1.6nF of integrated capacitance acts as a local power supply. The isolated V_{DD} drops by 0.5V when the radio transmits one bit every 131μs and is recharged between transmissions.

The desired IOPM lifetime is years to converge on a suitable glaucoma treatment. However, the anterior chamber volume limits lifetime by constraining the size and capacity of the microsystem's power sources [7]. The IOPM uses a custom 1μAh thin-film Li battery from Cymbet. The lifetime is 28 days with no energy harvesting. To extend lifetime, the IOPM harvests light energy entering the eye with an integrated 0.07mm^2 solar cell and recharges the battery. Given the ultra-small solar cell size, energy autonomy requires average power consumption of <10nW. Processor power is reduced using subthreshold operation and delivered using an SCN with 75% efficiency (Fig. 17.6.6). The SCN uses reduced swing clocks and level converters (LCs). While IOP measurements and wireless transmissions require μWs and mWs of power, these events are short and infrequent. When CDC and radio circuits are idle, their power consumption drops to 172.8pW and 3.3nW, respectively. For the majority of its lifetime the IOPM is in a 3.65nW standby mode where mixed-signal circuits are disabled, digital logic is power-gated, and 2.4fW/bitcell SRAM retains IOP instructions and data [5]. The average system power with pressure measurements every 15 minutes and daily wireless data transmissions, is 5.3nW. When sunny, the solar cells supply 80.6nW to the battery. The combination of energy harvesting and low-power operation allows the IOPM to achieve zero-net energy operation in low light. The IOPM requires 10 hours of indoor lighting or 1.5 hours of sunlight per day to achieve energy-autonomy.

Acknowledgments:
We gratefully acknowledge Cymbet Corporation for supplying a custom-size battery for this application.

References:
[1] K.C. Katuri, S. Asrani, and M.K. Ramasubramanian, "Intraocular pressure monitoring sensors," *IEEE Sensors Journal*, vol. 8, no. 1, pp. 12-19, Jan. 2008.
[2] E.Y. Chow, et al., "Mixed-signal integrated circuits for self-contained sub-cubic-millimeter biomedical implants," *ISSCC Dig. Tech. Papers,* pp.236-237, Feb. 2010.
[3] D.G. Vaughn, T. Asbury, P. Riordan-Eva, *General Ophthalmology*, 15th ed. Stamford, CT: Appleton & Lange, 1999.
[4] R. M. Haque and K. D. Wise, "An intraocular pressure sensor based on a glass reflow process," *Solid-State Sensors, Actuators, and Microsystems Workshop*, pp. 49–52, 2010.
[5] G. Chen, et al., "Millimeter-scale nearly perpetual sensor system with stacked battery and solar cells," *ISSCC Dig. Tech. Papers,* pp.288-289, Feb. 2010.
[6] R. Harrison, et al., "A low-power integrated circuit for a wireless 100-electrode neural recording system", *ISSCC Dig. Tech. Papers*, pp. 555-556, Feb. 2006.
[7] A.C.-W. Wong, et al., "A 1V, micropower system-on-chip for vital-sign monitoring in wireless body sensor networks", *ISSCC Dig. Tech. Papers*, pp. 138-139, Feb. 2008.

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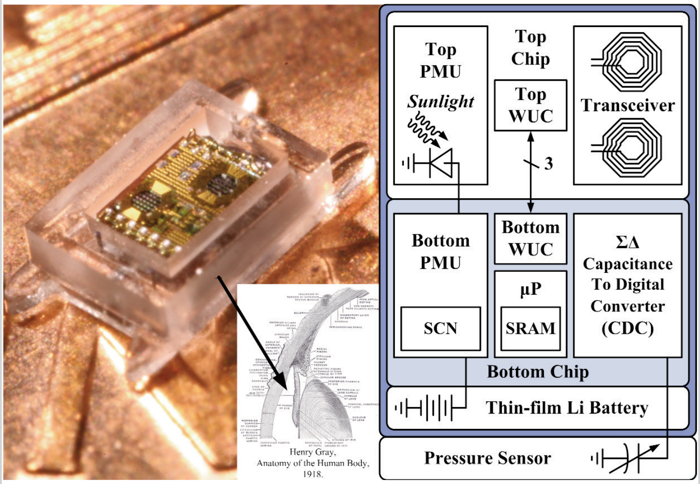


Figure 17.6.1: The IOPM contains a MEMS pressure sensor, integrated solar cell, and microbattery in a biocompatible enclosure. Its cubic-millimeter size enables implantation through a minimally invasive incision.

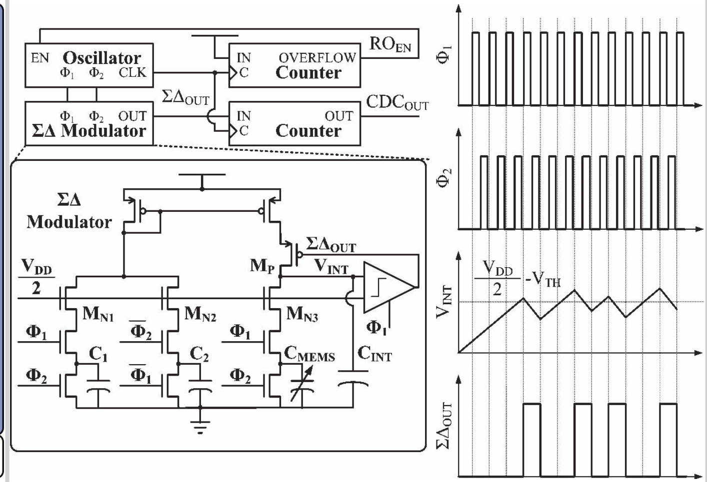


Figure 17.6.2: The capacitance to digital converter compares pressure-dependent and fixed currents using ΔΣ modulation. The design style provides independence to supply voltage and clock frequency uncertainty.

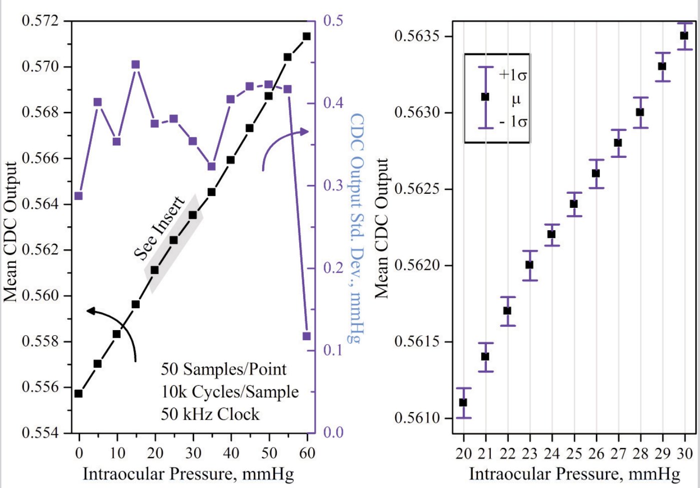


Figure 17.6.3: Measured results demonstrate CDC performance. The IOPM exceeds typical measurement techniques by achieving 0.5mmHg pressure resolution.

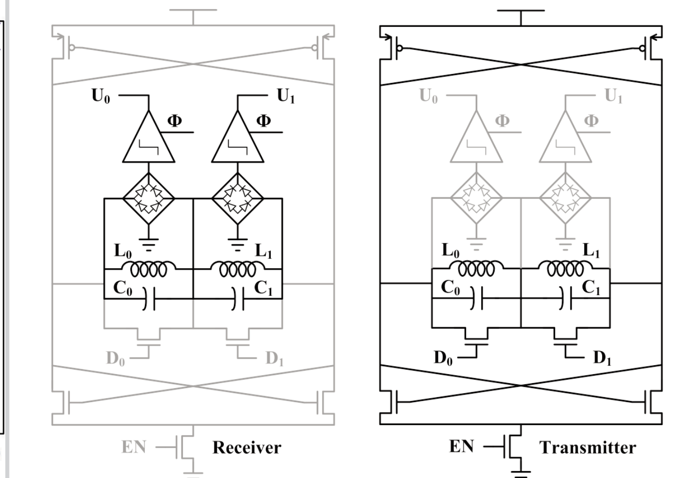
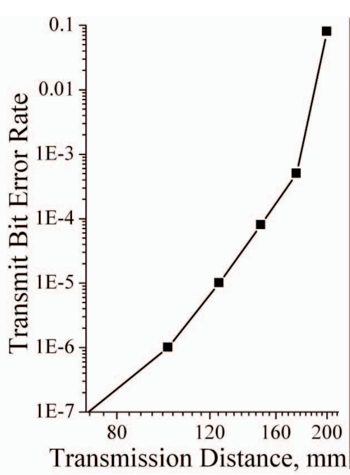
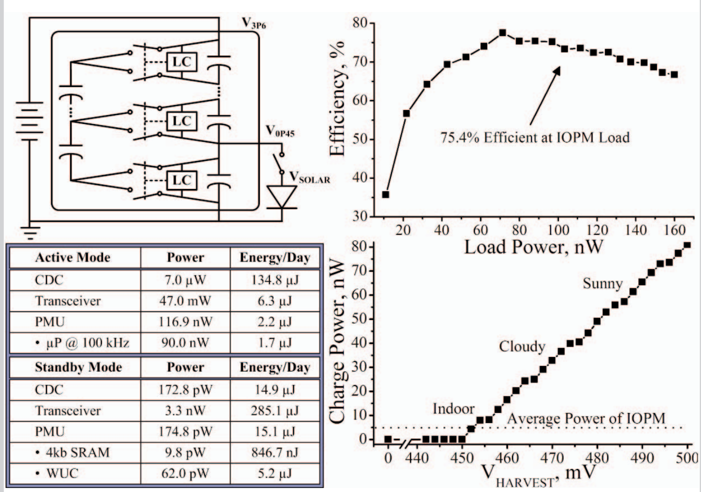


Figure 17.6.4: The series-connected LC tanks: (1) enable greater frequency separation than a single tank transmitter, relaxing phase noise requirements, and (2) reduce area compared to two separate LC tanks.



	This Work	[2]	[6]
Antenna Integration	On-chip	Off-chip	On-chip
Antenna Size	0.41 mm (2 coils)	27 mm	0.47 mm
Transmit Distance	10 cm	-	13 cm
Transmit Medium	5 mm Saline + Air	Air	Air
Bit Error Rate	1E-6	1E-5	3E-3
Peak Power	45.7 mW	1.1 mW	6.7 mW
Energy per Bit	4.7 nJ	27.2 nJ	20.4 nJ

Figure 17.6.5: The IOPM is activated when it receives and rectifies the wireless wake up signal. The device then transmits pressure data with a BER of less than 10^{-6}.



Active Mode	Power	Energy/Day
CDC	7.0 µW	134.8 µJ
Transceiver	47.0 mW	6.3 µJ
PMU	116.9 nW	2.2 µJ
• µP @ 100 kHz	90.0 nW	1.7 µJ
Standby Mode	**Power**	**Energy/Day**
CDC	172.8 pW	14.9 µJ
Transceiver	3.3 nW	285.1 µJ
PMU	174.8 pW	15.1 µJ
• 4kb SRAM	9.8 pW	846.7 nJ
• WUC	62.0 pW	5.2 µJ

Figure 17.6.6: IOPM power consumption is 5.3nW with the expected usage model. Energy autonomy is achieved with a 0.07mm² solar cell that supplies 80.6nW to the battery. Battery life without recharge is 28 days.

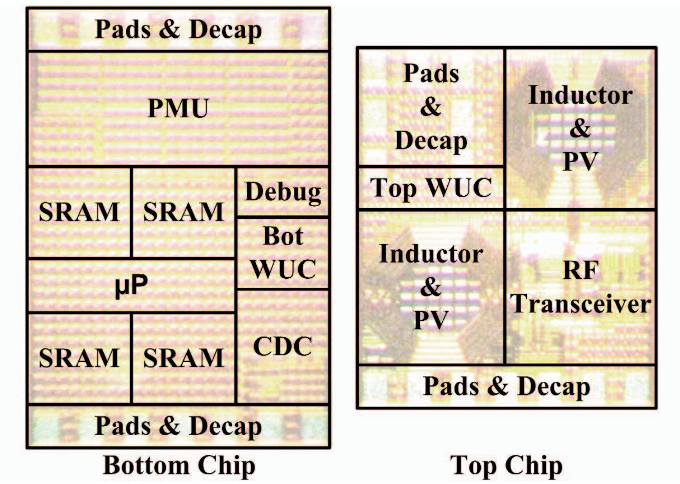


Figure 17.6.7: Die photographs for the bottom and top chips as defined in Figure 17.6.1, both fabricated in 0.18µm CMOS.

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