A 10mm^3 Light-Dose Sensing IoT^2 System with 35-to-339nW 10-to-300klx Light-Dose-to-Digital Converter

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Abstract

This paper presents a 10mm^3 Internet-of-Tiny-Things (IoT^2) system that measures light dose using custom photovoltaic cells and a light-dose-to-digital converter (LDDC). The LDDC nulls diode leakage for temperature stability and creates headroom without power overhead by dual forward-biased photovoltaic cells. It also adaptively updates the current mirror ratio and accumulation weighting factor for a low, near-constant power consumption. The system can operate energy-autonomously at >500lx light level. The LDDC achieves a 3σ inaccuracy of ±3.8% and σ/μ of 2.4% across a wide light intensity range from 10lx to 300klx while consuming only 35 – 339nW.

Introduction

Millimeter-scale Internet-of-Tiny-Things (IoT^2) systems open new capabilities in a variety of application spaces such as biomedical, security and energy exploration [1]. Cumulative light exposure (light dose) is a compelling parameter for IoT^2 since it can affect psychological and physical health, growth rates and product quality. The main challenge in developing light-dose sensing IoT^2 system is limited available power (<100nA) due to battery size constraint. To continuously record light dose without duty cycling, a low-power light-dose-to-digital converter (LDDC) is critical. Previous light sensors typically consumes >4µW ([2], [3]), which far exceeds the IoT^2 power budget.

Proposed Circuit

In this paper, we presents a 10mm^3 light-dose sensing IoT^2 systems using a new low-power LDDC that consumes only 35 – 58nW at <500lx ambient light condition. With integrated custom photovoltaic (PV) cells, the entire system achieves energy-autonomy at >500lx. The LDDC achieves a 3σ inaccuracy of ±3.8% across 23 chips from 10 – 300klx. Also, we demonstrate fully wireless operation of the LDDC when integrated in a millimeter-scale, complete IoT^2 sensor system, including a processor, power management unit, RF transmitter, wireless transceiver and battery.

A conventional light-to-digital converter uses the reverse biased current of a photo diode (PD) as an indicator of light intensity (Fig. 1). This biasing method provides a simple read-out of the current and removes voltage dependency. However, the amplifier that supports the PD current requires µW power consumption under strong light. Also, the photodiode leakage current perturbs the readout current and is strongly temperature dependent. Instead, the proposed LDDC uses a forward-biased PV cell and applies a zero bias-voltage (0V across PVS, Fig. 1) nulling the temperature dependent diode leakage to enhance temperature stability. The amplifier regulating the zero bias-voltage requires headroom, which would entail significant additional power consumption. Hence, we place a second, larger PV cell (PVL) in series beneath the sensing PV cell, thereby creating headroom without additional power overhead. The supply only has to power the low-power AMP2. The two PV cells are fabricated on the same die as the custom harvesting PV cells and do not increase system size.

A second challenge in LDDC design is the 30,000× dynamic range of light that often results in very high power consumption at high light intensity conditions. To avoid this, we adaptively update the current mirror ratio of a current-to-frequency converter such that the converter maintains a frequency in a narrow range, resulting in a low, near-constant power consumption of the following frequency-to-digital converter. The near-constant current from the current mirror is converted to a clock signal (AFEOUT) by the current-to-frequency converter and then to a digital code by the frequency-to-digital converter. A monitoring counter checks that the frequency (and hence mirror current) remains within range and adjusts the current mirror ratio as needed. To account for the mirror ratio in the conversion to a digital code, the light-to-current converter adjusts its accumulation weight to match the mirror gain.

Fig. 2 shows the light-to-current and current-to-frequency converter details. PVL (2× larger than PVS) provides a ~0.2V cathode voltage (Vbase) for PVS. AMP1 regulates Vbase to Vref1 by pulling down current to ground (M1). At very dark conditions, the 100 pA current source guarantees stable regulation of Vbase. AMP2 controls M2 and regulates Vpv to Vbase to extract short-circuit while nulling leakage. M2 is designed with HVT transistors, and its reconfigurable switches suppress leakage current at weak light condition. Compared with short-circuit current from PVS, the leakage is only 0.56% at 10lx, 85^{o}C, FF corner (simulated, the worst case). The bias current of AMP2 is mirrored from M1, which is proportional to the light intensity. Mirroring the bias current in this way increases the feedback bandwidth of AMP2/M2 at high light-levels while maintaining robust stability. Although the bias current is proportional to light intensity, it is less than 20% of the short-circuit current of PVS. Even at 300klx, power consumption of the LDDC remains below 340nW which is easily supported by the separate IoT^2 PV harvester at those high light levels, maintaining energy autonomous operation. A reconfigurable current mirror (M2, M4, and M5) regulates current through M4 and M5, resulting in near-constant frequency at AFEOUT and low-power consumption across 16,384× brightness change. M6 and M7 form a second current mirror to extend the light-level coverage range to 131,072×. The output current (Icap) charges the capacitor C1 to Vref2, and a continuous comparator generates a pulse to discharge C1. For Vref1, Vref2, and the 100pA bias current, pW voltage references and bias current generators are included on chip [4].

Fig. 3 shows the frequency-to-digital converter and its adaptive reconfiguration. The monitoring counter measures AFEOUT frequency and adjusts the current mirror gain for frequency regulation. The output counter integrates AFEOUT with a weighting factor, which is updated simultaneously with the current mirror gain to compensate for the adjusted current value. To operate the FSM, a 5nW timer is included on chip [5].

Measurement Results

The LDDC circuit was fabricated in 180nm CMOS. The two PVs were fabricated in GaAs on a single custom die (Fig. 4). Fig. 5 – 8 show the measurement results of LDDC. The proposed LDDC achieves a 3σ inaccuracy of ±3.8% after individual 2-point & batch calibration across all the available 23 samples and σ/μ of 2.4% from 10 – 300klx while consuming only 35 – 339nW. It shows -2.5/1.3% variation across -20 – 85^{o}C and -0.42/0.27% across 3.6 – 4.2V supply.

The proposed LDDC and PV cells were integrated in a 10.1mm^3 complete sensor system (Fig. 9) with two batteries and 6 other IC layers implementing: processor, radio, power management, decap, and temperature sensor. An ARM Cortex-M0 processor and 8kB SRAM manages LDDC operation. The 3.8-to-4.1-V thin-film batteries power the LDDC while being recharged by the 8 series PV cells. The complete system operation, including the LDDC function, was confirmed using wireless communication (Fig. 10). Also, the system becomes energy autonomous at >500lx (office room light) while continuously recording light dose (Fig. 11). Table I shows a comparison table showing lowest power consumption except for [6], which does not report inaccuracy or supply sensitivity. Also, it is the only listed work showing results across 23 measured die demonstrating the robustness of the proposed approach.

References

[1] D. Blaauw, ISLPED, 2018. [2] Texas Instruments, "OPT3007."
[3] M. Alhawari, et al., JSSC, 2014. [4] I. Lee, et al., JSSC, 2017.
[5] T. Jang, et al., ISSCC, 2016. [6] W. Lim, et al., ISSCC, 2017.

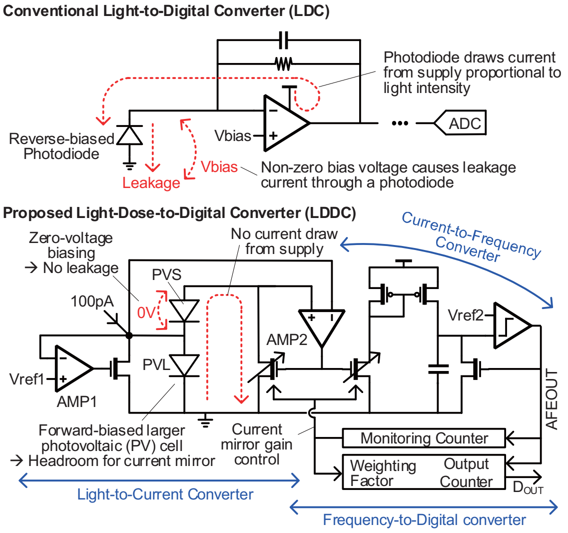

Figure 1. Conventional LDC (top) and the concept of the proposed LDDC (bottom).

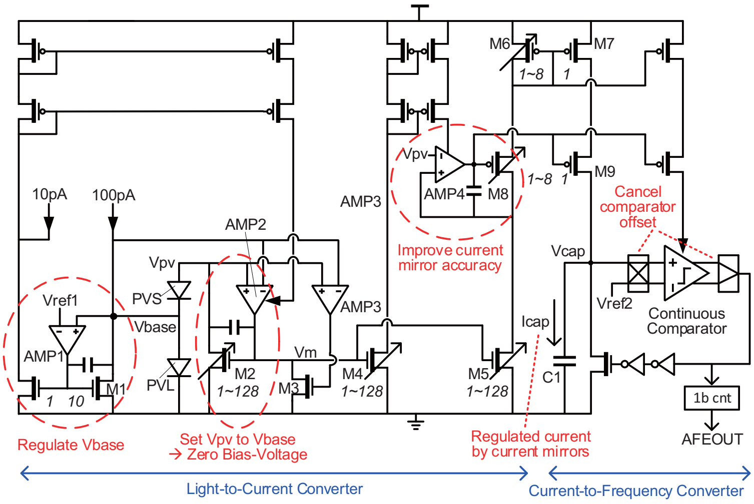

Figure 2. Proposed light-to-frequency conversion using dual PV cells.

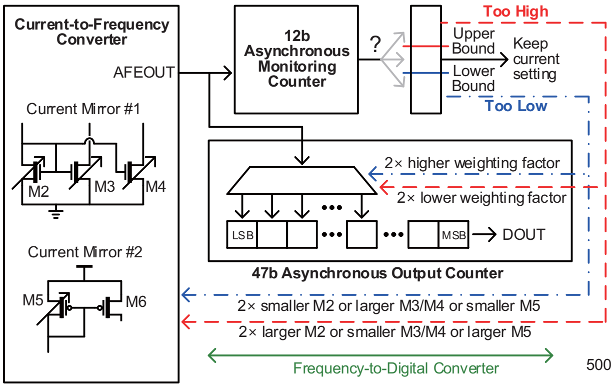

Figure 3. Proposed frequency-to-digital converter with adaptive operation for current mirror gain and weighting factor.

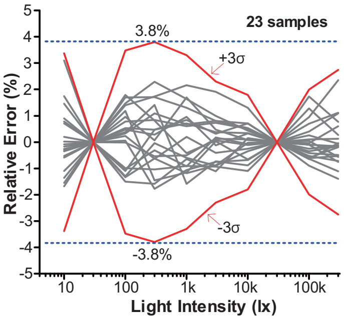

Figure 5. Measured inaccuracy.

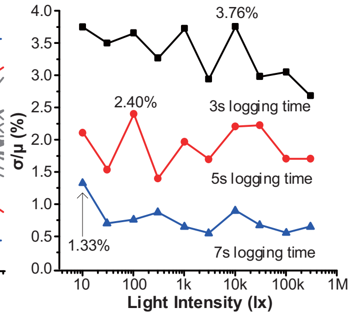

Figure 6. Measured σ/μ.

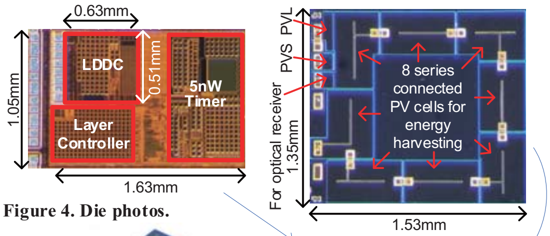

Figure 4. Die photos.

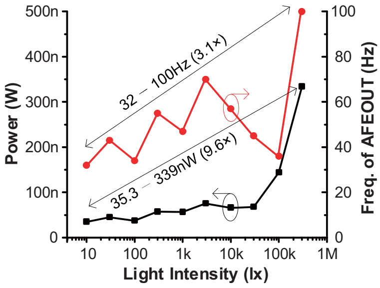

Figure 7. Measured power and frequency.

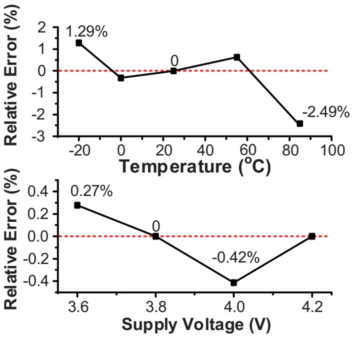

Figure 8. Measured dependency on temp. (top) and supply voltage (bottom).

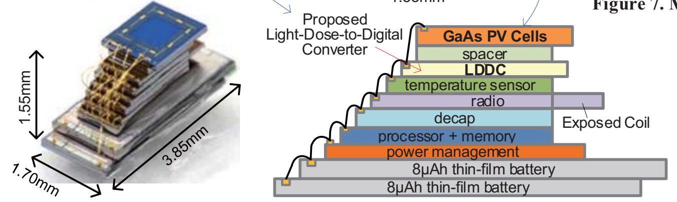

Figure 9. 10mm3 complete sensor system with the proposed LDDC. System photo (left) and diagram (right).

	This Work	[2] TI, OPT3007	[3] JSSC 2014	[6] ISSCC 2017
Process	0.18μm CMOS	N/A	0.18μm CMOS	0.18μm CMOS
Conversion Method	Adaptive Freq. Regulation	VGA + 12b ADC	DRC + LIQAF	DLS OSC
System Integration	Yes	No	No	No
Power	35.3−339nW	6.5−13.3μW	4μW	0.55nW
Inaccuracy	±3.8% @ 10 – 300klx	2% @ 40 – 84klx	N/A	N/A
# Samples	23	N/A	1	1
Measurement Time	5s	800ms	N/A	7.5s
Resolution	2.4% (σ/μ)	N/A	0.45% (σ/μ)	2.8% (σ/μ)
Temperature Sensitivity	0.036%/°C @ 1klx (w/ PV cell)	0.1%/°C @ 2klx (w/ photodiode)	N/A	0.065%/°C @ 500lx (w/o PV cell)
Supply Sensitivity	1.15%/V	0.1%/V	N/A	N/A

*10lux to 300klx → twilight to direct sunlight.

Table I. Performance summary and comparison.

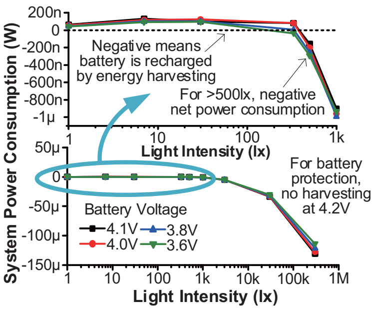

Figure 10. Measured system power.

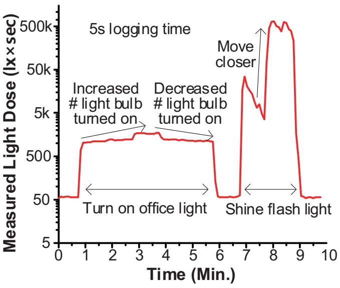

Figure 11. Measured light dose from the complete system.