A Light Tolerant Neural Recording IC for Near-Infrared-Powered Free Floating Motes

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Abstract

A key challenge for near-infrared (NIR) powered neural recording ICs is to maintain robust operation in the presence of parasitic short circuit current from junction diodes when exposed to light. This is especially so when intentional currents are kept small to reduce power consumption. We present a neural recording IC that is tolerant up to 300 μW/mm^2 light exposure (above tissue limit) and consumes 0.57 μW at 38°C, making it lowest power among standalone motes while incorporating on-chip feature extraction and individual gain control.

Introduction

Power transmission and communication are the key challenge for ultra-small (< 0.5mm) wireless neural recording motes and, among several approaches (RF, ultra-sound [1,2]), NIR using an integrated PV and LED is unique in its ability to scale linearly to very small sizes (< 100μm) [3,4]. Minimum size is critical to achieving dense recording arrays and minimum scarring and requires that radiated light power is maximized while chip power and currents are minimized. This leaves the circuits particularly susceptible to light-induced parasitic currents (Fig. 2). In conventional chips, light is blocked with an encapsulant. However, a partly transparent encapsulation that exposes the PV and LED while blocking light for sensitive circuits is infeasible at sub-mm scales leaving the solution to light tolerant circuit design. To our knowledge, this work is the first attempt to address this challenge.

The proposed IC achieves robust operation past the tissue limit NIR (150 μW/mm^2) while a baseline implementation fails at 8μW/mm^2. The chip maintains sub-μW power while incorporating advanced functionality, including on chip feature extraction and gain control. The proposed work was tested with neural signals from a Long Evans rat and demonstrated high fidelity monkey finger motion decoding.

The envisioned system architecture is described in [4] and consists of a large number of free-floating motes on top of the brain that use NIR for power delivery, uplink and downlink to a repeater unit outside the dura (Fig.1). Each mote consists of a custom GaAs chip with dual junction PV (I_{SC} > 1.1μA, V_{OC} = 1.6V at 150μW/mm^2 850nm light, measured) and LED sandwiched on top of the CMOS chip with an attached carbon fiber penetrating the brain to obtain neural signals.

Proposed Circuit

The IC consists of a three-stage-amplifier for neural signal acquisition, signal processing that extracts a neural feature called spiking band power (SBP) [5], a pulse gap modulator (PGM) and LED driver for data uplink, and an optical receiver (ORx) for data downlink followed by clock and data recovery (Fig. 3). A pseudo resistor (R_{PSD}) is frequently use for DC-feedback since its high, TΩ resistance [3,4] can achieve the demandingly low high-pass corner and reduces resistor noise. However, its extremely low conductance, G_{FB}, also makes it susceptible to junction to substrate and deep n-well to p-well photo generated current (I_{SC_P}) (Fig. 4, left). This low conductance vs. I_{SC_P} results in a poor *light robustness ratio* ($R_{LR} = G_{FB} / I_{SC\_P}$) and the DC-bias level will drift at < 1μW/mm^2 (simulation). A series-to-parallel switched capacitor-based resistor [7] was proposed to address the process sensitivity of R_{PSD}. However, while it has higher conduction, its high number of switches results in a large total junction area and high I_{SC_P} and R_{LR} remains poor (Fig. 4, mid). Instead, this work adopts a hybrid approach combining a simple switched capacitor resistor with a 3× attenuator. It maintains a much larger G_{FB} while having a lower I_{SC_P} resulting a $5{\cdot}10^4$× improvement in R_{LR} and achieves light tolerance till 350μW/mm^2 in simulation (Fig. 4, right).

The amplifier achieves 68 dB peak gain, [380, 1060] Hz bandwidth, > 67dB of CMRR and PSRR and, IRN of 6.2μV_{RMS} with 150μW/mm^2 of incident 850nm LED light at 38°C in measurement which is nearly unchanged from that measured without light (Fig. 5, table). The graph in Fig. 5 plots measured gain across light level for a baseline R_{PSD} and proposed structure showing that while the baseline structure fails at 8μW/mm^2, the proposed structure stays stable till 300μW/mm^2.

Spiking band power (SBP) is a neural feature used for motor prediction and is defined as average of absolute signal amplitude in 300-1000Hz [5]. The analog SBP extraction in [4] is compact, but relies on tens of pA of on-current to charge an integration capacitor, which is susceptible to I_{SC_P}. We instead propose an area-efficient and light tolerant *digital* SBP extraction unit using a flash ADC. It consists of a diode-stack-based V_{REF} generator (12nA, simulation), dynamic comparators with staggered clocks, followed by pulse generators. An asynchronous counter accumulates the total number of fired pulses which integrates the absolute amplitude over the pulse width (Fig. 6, 7). By comparing the counter to a threshold, SBP is symbol-interval-encoded (LED_EN, Fig. 6). LED_EN then fires the LED with a pulse-gap-modulated (PGM) encoding of the mote ID (Fig. 3). Each LED packet consists of a total 17 pulses where the pulse gap ($2*T_{CLK}$/$3*T_{CLK}$ for data 0/1) encodes the 10b unique chip ID (from PUF [6]) and 6b gain configuration (Fig. 10). The LED driver consumes 76nW (simulation) at 50Hz LED firing rate.

The ORx allows for data downlink and remote gain control (RGC) (Fig. 9). Two matched 2T-VRs [8] provide DC-bias to the inputs of a hysteretic comparator, AC coupled to V_{DD} and GND. Light modulation toggles the comparator which drives clock and data recovery. The 2T-VRs are size for 1.4nA (simulation) to ensure light robustness, eliminating the light sensitive R_{PSD} bias in [4].

Measurements

The proposed IC was fabricated in 180nm CMOS (Fig. 11). In a fully wireless optical setup with an NIR laser for power transfer and downlink and SPAD detector for uplink reception (Fig. 10) the IC with custom PV/LED GaAs chip wirebonded side-by-side was fully functional. The LED_EN signal was successfully decoded from the measured SPAD output using the 16b match filter, shown in Fig. 10.

In vivo measurement using a carbon fiber inserted into the brain of an anesthetized Long Evans rat and wired to the CMOS chip verified the proposed SBP extraction. Compared to SBP measurement with a high-power commercial recording/signal-processing system, the proposed chip shows good accuracy for motor function decoding (Fig. 8). All procedures complied with the University of Michigan's Institutional Animal Care and Use Committee.

Finger movement of a monkey was predicted using a 20-channel-prerecorded motor cortex signal and the resulting SBP from the IC with both fixed gain and off-chip RGC (based on average LED firing rate, Fig. 12a). A Kalman filter was used for training with the first 100s and predicting the next 24s of the movement. The proposed SBP successfully predicted the movement (Fig. 12b) with only slight accuracy degradation. With RGC, accuracy improves by several percent and LED firing rate remains below 50Hz across all the channels, allowing for increased channel utilization.

Table I compares the IC to state-of-the-art standalone wireless recorders. Only optical units scale below 0.5 mm and only the proposed optical mote can fully function under 300μW/mm^2 of light exposure. It also achieves the lowest power consumption of 0.57μW at 38°C with 4.1 NEF, pseudo-resistor-less amplifier, on-chip SBP extraction in digital domain, and individual mote downlink for RGC.

Acknowledgements

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References

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[5] S. R. Nason, *et al.*, Nature BME, Jul. 2020.
[6] K. Yang, *et al.*, ISSCC, 2017. [7] N. Verma, *et al.*, JSSC, Mar. 2010.
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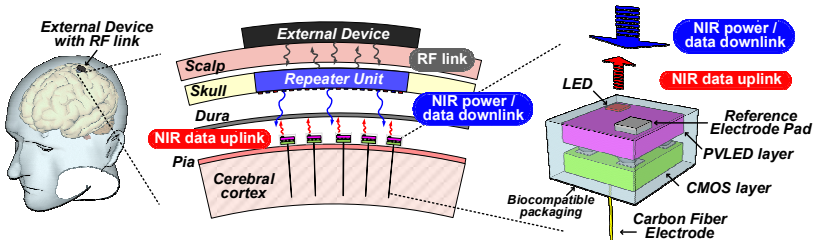

Fig. 1. Conceptual illustration of NIR based wireless neural recording motes

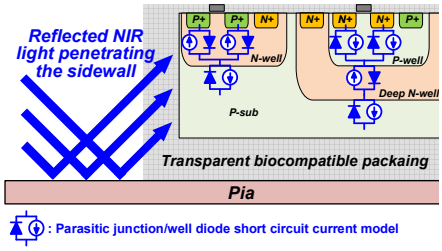

Fig. 2. Cross section of the CMOS layer with parasitic diode short circuit currents

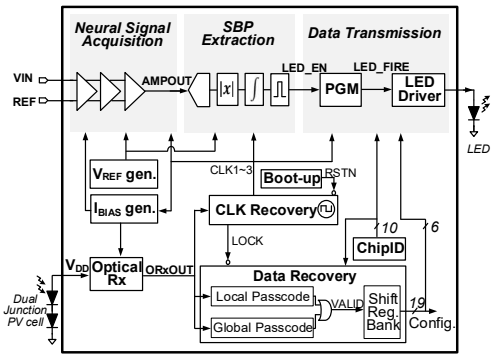

Fig. 3. Top circuit diagram of the CMOS layer

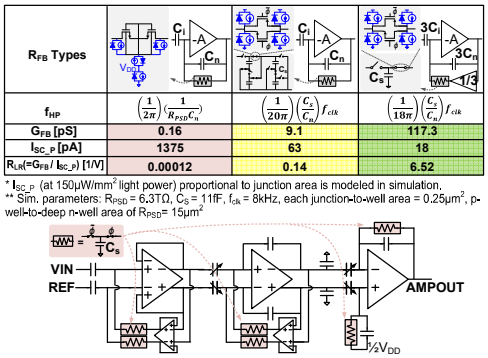

Fig. 4. Simulated light robustness of three different feedback resistors (top) and proposed light tolerant amplifier (bottom)

	Light OFF	Light ON(150μW/mm²)
Peak Gain [dB]	67.2	68.0
CMRR [dB]	69.7	72.2
PSRR [dB]	67.5	69.2
BW [Hz]	[350,1080]	[380,1060]
ORN [mVRMS]	12.7	13.5
IRN [μVRMS]	6.2	6.2

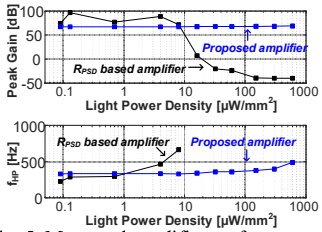

Fig. 5. Measured amplifier performance with 850nm light (IRS4, CMVision)

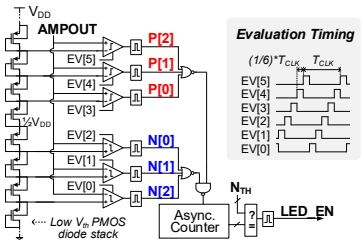

Fig. 6. Flash ADC and pulse-counter-based SBP computing unit

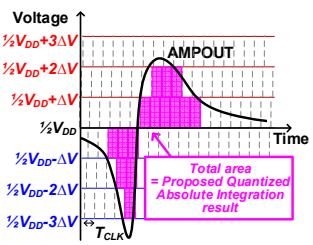

Fig. 7. Quantization of absolute amplitude and width from the SBP computing unit

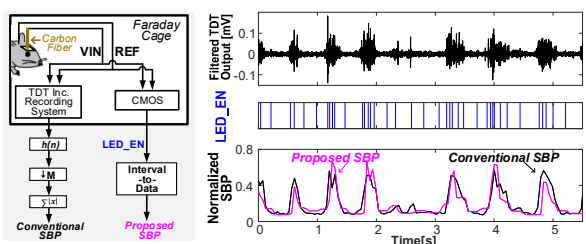

Fig. 8. *In vivo* measurement setup with RA16PA pre-amp and RX7 Pentusa base station from TDT Inc. (left) and measured waveforms (right)

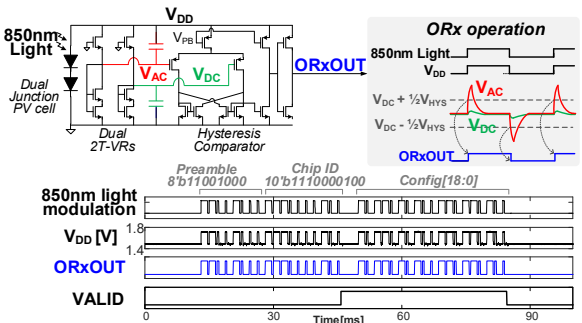

Fig. 9. ORx structure and operation (top), and measured selective programming waveforms from wireless optical setup (bottom)

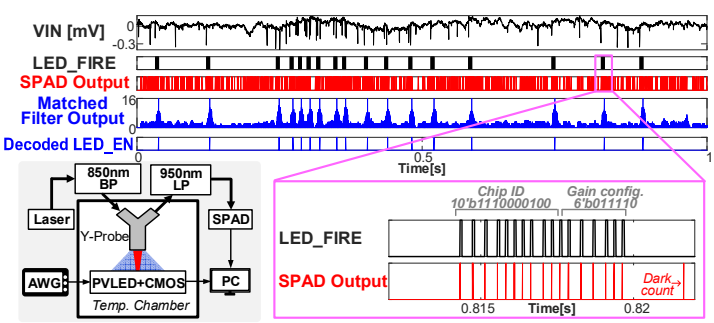

Fig. 10. Measured matched filter decoding result (top), and wireless optical setup with NIR laser (QFLD850200S, Qphotonics) and SPAD (SPDOEMNIR, Aurea) (bottom, left)

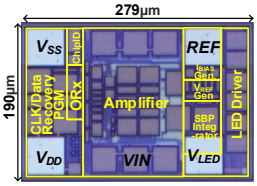

Fig. 11. Die photo

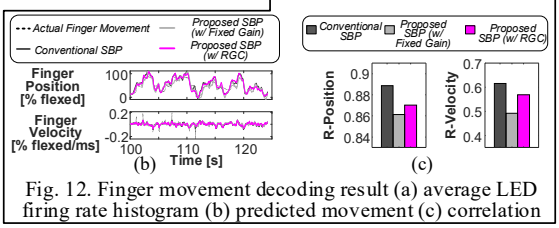

Fig. 12. Finger movement decoding result (a) average LED firing rate histogram (b) predicted movement (c) correlation

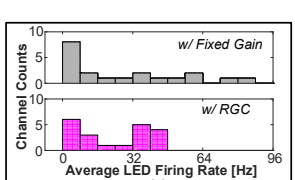

Table I. Comparison table

		This work	[4]	[3]	[1]	[2]
Technology [nm]		180	180	180	65	65
Wireless Method		Optical	Optical	Optical	RF	Ultrasonic
Area [mm²] (W [mm] x L [mm])		0.053 (0.19 x 0.28)	0.032 (0.19 x 0.17)	0.014 (0.25 x 0.06)	0.250 (0.50 x 0.50)	0.250 (0.50 x 0.50)
Data Link	Uplink	PGM-SIM	Macnchester-SIM	PPM	RF	AM
	Downlink	PWM	PWM	No	ASK-PWM	No
	Mote-Level Gain Control	Yes	No	No	No	No
On-chip Feature Extraction		SBP (digital)	SBP (analog)	No	No	No
Chip ID		Yes	Yes	No	Yes	Yes
Clock Recovery		Yes	Yes	No	No	No
Use of Pseudo Resistor		No	Yes	Yes	No	No
Light Tolerant Design (max. light power density)		Yes (300μW/mm²)	No	No	N/A**	N/A**
Supply [V]		1.55	1.5	0.9	0.6	1
Power	Total [μW]	0.57*	0.74*	1	40	28.8
	Amplifier [μW]	0.36*	0.51*	0.5	3.2	4
Target neural signal		AP	LFP, AP	ECoG	LFP, AP	
Gain [dB]		67.2*	69.0*	30.0	N/A	24.0
Bandwidth [Hz]		[350, 1080]*	[180, 950]*	10000	500	5000
NEF		4.10*	3.76*	4.31	8.70	5.87

* Measured at 38°C ** Not Applicable