26.9 A 0.19-0.17mm² Wireless Neural Recording IC for Motor Prediction with Near-Infrared-Based Power and Data Telemetry

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Brain machine interfaces using neural recording systems [1–4] can enable motor prediction [5–6] for accurate arm and hand control in paralyzed or severely injured individuals. However, implantable systems have historically used wires for data communication and power, increasing risks of tissue damage, infection, and cerebrospinal fluid leakage, rendering these devices unsuitable for long-term implantation (Fig. 26.9.1, top). Recently, several wireless and miniaturized neural recording implants with various power and data transmission methods were proposed. References [7,8] propose an electrocorticography (ECoG) recording system with near-field RF power transfer and bilateral communication, but the 0.5W Tx exceeds maximum exposure limits by 10x [8]. Ultrasound telemetry can safely send more power than RF; however it requires mm-scale dimensions (0.8mm² in [9]) due to bulky ultrasound transducers. On the other hand, near infrared (NIR) light can provide power transfer and data downlink via a photovoltaic cell (PV), and a data link via a light-emitting diode (LED). Dimensions can be scaled to 100s of microns [10], with [11] demonstrating a 0.0297mm² neural recording system using a 50mW/mm² light source (<1/6th of safety limit for the brain). However, this system is limited to a single channel, and since it only has a surface electrode, it can record only surface potentials (face-down, potentially blocking the light channel) or must itself be injected into brain tissue, creating significant tissue damage and danger of bleeding. In this paper, we propose a 0.74μW, 0.19±0.17mm² IC designed for a wireless neural recording probe. It computes so-called spiking band power (SBP) [5,12] on-chip to save 920+ power while maintaining accurate position and velocity decoding.

A neural probe IC is designed for a larger neural recording system concept (Fig. 26.9.1, bottom) in which numerous micro-probes would be placed on the brain in the sub-dural space to record neural spikes using a carbon fiber electrode that penetrates several mm into brain tissue and has been shown to incur minimal chronic scar formation [13]. The probes will be powered and globally programmed by 850nm NIR light emitted by a repeater placed in the epidural space. The LED in the probe will act as the data uplink; its light received by the repeater using a single-photon avalanche diode (SPAD). The repeater would service 100s of probes, which are distinguished by their on-chip ID and location. Given its larger size, the repeater can use an inductive link for wireless power and data communication with an external receiver.

The CMOS IC consists of an optical receiver followed by clock and data recovery, a random-number-generated-based chip ID [14], neural recording amplifier, SBP extractor, and LED driver (Fig. 26.9.2). Figure 26.9.3 shows the schematic and measured signal diagram of the optical receiver (ORx). The IC is AC-coupled to a comparator input to convert modulated light from the repeater to a digital signal. The comparator has 80mV hysteresis to remove glitches due to unwanted VDD fluctuations. In the power-on reset phase, the clock recovery circuit locks the on-chip clock to the precise 8kHz modulated light from the repeater. This is critical since the clock is used to set the reference current, which must be precisely controlled for reliable amplification and signal filtering. The clock recovery circuit searches the digitally-controlled oscillator (DCO) thermometer-coded configurations to match the received modulation period with the DCO period. Then it switches the system clock from the default to recovery clock using glitch-free multiplexers. After clock locking, the repeater programs the system using pulse width modulated (PWM) light (downlink). An 8b hardwired passcode is implemented to prevent unwanted programming. The signal diagrams in Fig. 26.9.3 are measured from the proposed chip, wire-bonded with a custom dual-junction GaAs PV cell that generates 893nA ISC and 1.67V VOC under 120.5μW/mm² 850nm light.

The AFE is specifically designed to support SBP [5] based finger position / velocity decoding. SBP is the absolute average of signal amplitude in the 300-to-1000Hz band. When used as input to a trained linear decoding filter, SBP maintains finger position / velocity decoding accuracy relative to a standard 7.5kHz bandwidth neural recording while reducing the required communication bandwidth from probe to repeater to only 100s of Hz, thereby reducing uplink power. The AFE is composed of a three-stage bandpass differential amplifier chain with subsequent source follower and rectifier-based integrator to quantize the SBP (Fig. 26.9.4 left). The LNA, with 60Ω input impedance at 1kHz, is fully differential and achieves 30dB gain without bulky capacitors by implementing its gain using gm ratio. VGA1 and VGA2 set the high-cut-off (fH, 950Hz) and low-cut-off frequencies (fL, 1800Hz), respectively, and define the spiking band. fH is set by VGA2 bias current, which is generated by a current reference implemented using a voltage reference and switched capacitor operating at fCLK. fL is defined by the VGA2 DC servo loop whose feedback impedance is defined by 1/C1*CfM. Accuracy of fH and fL is ensured by locking fCLK during clock recovery to the repeater. Peak gain is measured at 69dB while amplifying action potential (AP) spikes in 180–950Hz bandwidth for SBP-based motor prediction. Measured input-referred noise (IRN) is 4.8μVrms while consuming 510nW at 38°C.

The 3-stage amplifier drives a rectifier (Fig. 26.9.4 bottom left) whose output is initially precharged to VREF+. The rectifier output decays at a rate proportional to its input amplitude. When it drops below VREF−, a pulse is generated on VOUT. This triggers the LED driver to transmit a Manchester encoded (unique) chipID (Fig. 26.9.5 top left) consuming 6.7μJ/bit (post layout simulation). Therefore, the LED firing rate or frequency is proportional to the SBP. AFE functionality was also verified in vivo using a carbon fiber driven –1.3mm into the motor cortex of an anesthetized Long Evans rat. A commercial recording system (24.41kHz, 2.2Hz, 7.5kHz BW) is connected to the carbon fiber electrode in parallel to the IC for accuracy comparison. All procedures compiled with the Institutional Animal Care and Use Committee. VIN is the input of the proposed amplifier, measured by the high-power commercial recording system. VOUT(VOUT+−VOUT−) is the amplifier measured output. Results show that the rectifier output (INTOUT) steps down at each motor cortex neuron spike and is restored to VREF when it reaches VREF (Fig. 26.9.4).

LED firing rate linearity across SBP is tested using synthesized AP spikes (240μVA−to−A+, 1ms width) with varying rates from 0 to 100Hz (Fig. 26.9.5 top right). The measured LED firing rate is proportional to SBP with nonlinearity <2.9% and its sensitivity is programmable from 0.4 to 5.0 firings per μV. Overall functionality is verified using three different types of input signals; synthesized neural simulator, in vivo rat motor cortex, and pre-recorded monkey motor cortex (Fig. 26.9.5 bottom). Measured probe SBP is decoded from the measured time interval of LED_EN signal and compared with the result generated by a conventional high-power analog front-end and DSP SBP calculation [5]. The measured probe SBP accurately matches the conventional system results. Figure 26.9.6 (top) shows fingerprint / velocity decoding results using Kalman-Filter (KF) [6] with conventional and probe SBP from pre-recorded 20-channel neural signals of a male monkey. All procedures compiled with the Institutional Animal Care and Use Committee. The system accurately predicts fingerprint / velocity with state-of-the-art correlation coefficient of 0.8587 / 0.5919 while a conventional high-power and wired system demonstrates 0.8886 / 0.6153 correlation coefficient. The IC is fabricated in 180nm CMOS (Fig. 26.9.7). Figure 26.9.6 (bottom) compares to previously published wireless neural probe chip designs. It consumes 0.74μW with 3.76 amplifier NEF at 1.5V supply and 38°C, achieving best noise performance among comparable designs [7,9,11].

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References:
Figure 26.9.1: Conventional and proposed neural recording system (top); concept diagram of proposed neural probe and two-step approach for recording and transmitting neural signals (bottom).

Figure 26.9.2: Top-level circuit diagram of the neural recorder.

Figure 26.9.3: Optical receiver (top left), clock recovery circuit (top right), data recovery structure (bottom right), and measured signal diagram during clock and data recovery (bottom left).

Figure 26.9.4: Amplifier (top left), rectifier based analog integrator (bottom left), measured amplifier AC and noise performance (top right), in vivo measurement results from a motor cortex of rat (bottom right).

Figure 26.9.5: Measured timing diagram of Manchester encoded chip ID (top left), measured linearity of LED firing rate across SBP (top right), and measured transient waveform from three types of input neural signals (bottom).

Figure 26.9.6: Finger position / velocity decoding result using KF with the probe and conventional SBP with pre-recorded 20-channel neural signals of a monkey (top) and comparison table (bottom).
Additional References:


