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IBCOM (Intra-Brain Communication) Microsystem: Wireless Transmission of Neural Signals within The Brain

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***Abstract*—we report our preliminary work to explore a new method of signal transmission for bio-implantable microsystems. Intra-brain communication or IBCOM is a wireless signal transmission method that uses the brain itself as a conductive medium to transmit the data and commands between neural implants and data processing systems outside the brain. Two miniaturized IBCOM (μ-IBCOM) CMOS chips were designed and fabricated for an *in vivo* test bed to transmit two prerecorded neural signals at different binary frequency shift keying (BFSK) carrier frequencies to validate the feasibility of IBCOM concept. The chips were packaged for full implantation in a rat brain except for external power delivery. The original neural signal waveforms were successfully recovered after being transmitted between two platinum electrodes separated by 15 mm with transmission power less than 650 pJ/bit for the CMOS implementation.**

I. Introduction

THE ability to record individual neuronal activities in the central and peripheral nervous systems has been an important tool in neuroscience research for decades. Recent technological advances have allowed the simultaneous recording of dozens to hundreds of neurons simultaneously [1-5]. While major advances have been achieved by numerous research groups over the last two decades [1-8], one of the long-sought, as yet unavailable goals in neuroscience is to acquire massive-parallel access of single neuron activities from many distributed probes inside the brain. One potential solution may be to develop a nano-scale fully-implantable Neural Recording/Stimulation System (NRSS) that is small enough to be located in any place of the brain without any detrimental tissue interaction and be able to record neural activities from one or more adjacent neurons or to stimulate them. However, critical stumbling blocks for this approach are in size scaling, power delivery, and effective signal transmission from these implants to the central data processing and analysis system located outside the brain. In this work we explored a new way of wireless signal transmission which can be realized using extremely low power in a small form factor.

Two standard methods for signal transmission between the implanted probes and an external waystation are through inductive coupling and RF telemetry [9-12]. RF transmission frequency is limited to several MHz to avoid tissue absorption in higher frequency signals. In addition, antenna size becomes a scale-limiting factor, especially when a low carrier frequency below 10 MHz is used for signal transmission. For inductive coupling, the signal transmission system requires the internal coil (inside the implant) to be aligned with the external coil (for receiving data) for maximum power transmission. This constrains the orientation of the implanted devices and limits the freedom of deployment. Therefore, it is difficult to realize the probe in a small form factor. Thus, both approaches are inherently unfavorable to be scaled toward an extremely small size below a hundred microns due to poor signal power transmission, large implementation size, and complicated circuitry required for operation.

We investigated a signal transmission mechanism using the brain itself as a conductive medium. In this work, we introduce IBCOM (Intra-Brain Communication) as a new way of communication between the implanted neural recording and stimulating system (NRSS) and external data collection stations. In the paper, we report a series of preliminary animal experiments using live rat brain to confirm the feasibility of IBCOM concept.

In Section II, the basic concept of IBCOM is presented with the details of signal transmission schemes. Section III describes the hardware design and implementation of CMOS chips for implant experiments. The *in vivo* experimental data and measurement results are discussed in Section IV, followed by the conclusion in Section V.

II. Intra-Brain Communication (IBCOM): Signal Transmission Through Brain Tissue

It would be ideal if a NRSS can be realized in an invisibly small size and be deployed in multiple (more than few hundreds of) neural probes scattered in the brain to monitor

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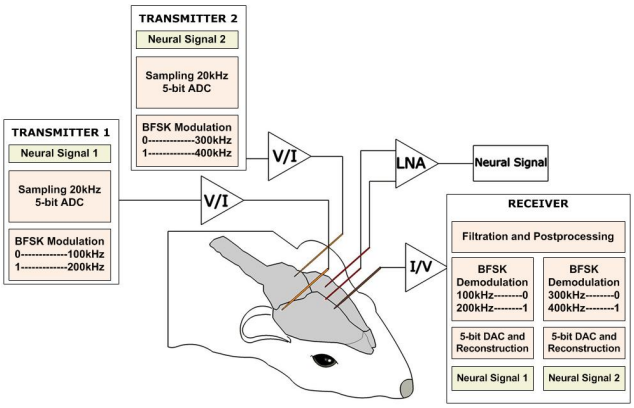

Fig. 1. Experimental setup of a two-channel IBCOM to demonstrate the transmission of modulated neural signals through the brain. Transmitters 1 and 2 send two different modulated neural signals, which are received by a single receiver. A low-noise amplifier (LNA) is used to record the live rat neural signal and to show the interference caused by IBCOM

adjacent neural activities and invoke stimulation when needed. Outstanding major milestones to build such a system include efficient power delivery, effective wireless signal transmission, and device scaling. In this section, we report our initial work on a low-power signal transmission scheme between the scattered neural probes and a receiving way-station located in the brain.

Fig. 1 shows a conceptual diagram of our initial experimental setup to test two-channels of intra-brain communication (IBCOM). In this experimental setup, we used the rat brain as a conductive media to transmit and receive two prerecorded neural signals. The system consists of two separate transmitters that send the modulated neural signals and one receiver. The purpose of this animal experiment was to verify the feasibility of IBCOM.

At each transmitter, a prerecorded neural signal was converted to serial 5-bit digital codes and then modulated and transmitted using Binary Frequency Shift Keying (BFSK). The two prerecorded neural signals were acquired from a separate recording experiment with 20 kHz sampling frequency. For the first IBCOM transmitter, the digital signal was modulated at 100 kHz for zeros and 200 kHz for ones, respectively, while for the second transmitter the signal was modulated at 300 kHz for zeros and 400 kHz for ones, respectively. Each modulated signal was then converted to current by a V/I converter and transmitted through two different Iridium Oxide (IrO_x) electrodes inserted in the rat brain. Since the animal is completely isolated from any grounded bodies, the only path of the transmitted current will be through the (third) IrO_x receiver electrode. (The third electrode served as the return electrode in this configuration.) The received current signal was then converted to voltage and separated into two signals using band-pass filters. Each signal was then BFSK-demodulated to retrieve the original analog neural signals.

In this experiment we tried different transmission currents sweeping from 2 $\mu A_{p\text{-}p}$ to 100 $\mu A_{p\text{-}p}$. The IBCOM transmitters were powered separately from each other using batteries (thus providing isolated/floating power sources). Separate battery power was also used for the receiver circuitry. From this initial animal experiment, we could successfully transmit and retrieve the signal at 2 $\mu A_{p\text{-}p}$ between the two electrodes separated by 15 mm, implying that the transmission power can be extremely small (less than 10μW). A low-noise amplifier (LNA) was used to record the live rat neural signal and to show the interference caused by IBCOM.

III. Miniaturized IBCOM CMOS Microsystem

We designed two different CMOS chips to test IBCOM functionality *in vivo*. The aim was to implant two chips in a rat brain; each of them simultaneously transmitting modulated neural signals at different frequencies. A receiving electrode should be able to receive and demodulate the transmitted signals to retrieve the original neural signals. We will refer to these two chips as μ-IBCOM1 and μ-IBCOM2, respectively.

A. μ-IBCOM CMOS Prototype Chips and Packaging

Fig. 2 shows a conceptual diagram of the μ-IBCOM prototype device. The chip was packaged in a silicon substrate with only three electrical connections: one signal transmission electrode and two power supply wires. The prototype chips were designed and fabricated using 0.25-μm CMOS technology. The active part of the chip is 400x270 μm^2. Biocompatible custom packaging was built for both μ-IBCOM chips to provide power and access to the brain for IBCOM transmission. The μ-IBCOM CMOS chips were attached to micromachined 40 mm long silicon spears to facilitate implantation in an anesthetized rat's brain. The silicon spears were diced from a 4 inch silicon wafer to have a small cross-section (500 μm x 500 μm) and a 15-degree chisel tip to minimize trauma to brain tissue during insertion. The silicon spears were coated with a 100 nm layer of alumina using atomic layer deposition. Three Teflon-insulated

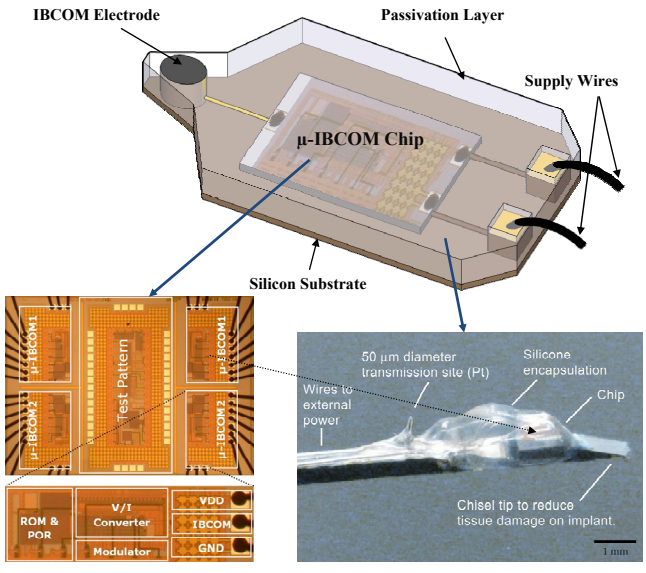

Fig. 2. IBCOM microsystem conceptual diagram (top), Microphotograph of four μ-IBCOM CMOS chips and a test pattern (bottom left), and μ-IBCOM packaging for full implantation in rat brain

platinum wires (50 μm) were attached to each silicon spear and wirebonded to the μ-IBCOM CMOS chip pads. Two of the wires extended the full length of the spear and were used to connect to a battery power source outside of the rat's brain. The third wire was bent perpendicular to the spear, stripped of insulation at the tip, and served as the transmission electrode. Finally, the μ-IBCOM CMOS chips and wirebonds were encapsulated with silicone (Dow Corning 3140 RTV).

B. CMOS Circuit Operation

Fig. 3 shows the components of the μ-IBCOM chip. The chip consists of a ROM array (to store neural signals), a BFSK digital modulator, and a voltage-to-current (V/I) converter. We implemented two μ-IBCOM chips: μ-IBCOM1 and μ-IBCOM2. The only difference in the design of these two chips is in the modulation frequencies and the ROM array contents. BFSK modulation frequencies of 100/200 kHz were used in μ-IBCOM1, and 300/400 kHz in μ-IBCOM2. Fig. 3 shows the two neural signals stored in the ROM of the two μ-IBCOM chips. They were prerecorded signals sampled at 20 kHz and converted to 5-bits digital signals. Each signal had a duration of 10 ms and ran continuously in a loop. This on-chip stored neural signal was modulated at each carrier frequency for current-mode signal transmission.

The digital output of the ROM was modulated using on-chip binary frequency shift keying (BFSK) modulation. The BFSK modulator design is based on a dual frequency ring oscillator. The BFSK modulator output is buffered and sent to the V/I converter. The supply voltage range (0 – 2.5V) was converted to ±10μA using the V/I converter circuit. The output current was connected to a transmitting electrode in the rat brain through the custom-designed package used for full implantation in the brain (as shown in Fig. 2).

IV. Measurement Results

A. Experiments Procedure

Multiple tests and experiments were conducted using both μ-IBCOM1 and μ-IBCOM2. A printed circuit board (PCB) was designed to test the performance of both chips in saline and rat brain. First, the μ-IBCOM1 and μ-IBCOM2 chips were integrated in the PCB and their outputs were connected to rat brain using two external platinum wires (with electrode size of 50μm in diameter). Signals from both chips were transmitted simultaneously and received at another location in the rat brain using a separate platinum microelectrode. The received signals were transferred to a standard PC through a DAQ card. A DSP algorithm was used to split the received signal into two separate signals using band-pass filter operation. Both signals were then demodulated and converted to analog signals. These retrieved signals were compared with the original signals stored in on-chip ROM.

Similar experiments were repeated using the fully-packaged version of the μ-IBCOM chips. In this case, the whole package was inserted into anesthetized rat brain by surgery. Power was delivered externally via two platinum wires (50μm diameter). The transmitted signal was received and demodulated using the same method described previously.

B. Fully Implanted μ-IBCOM Experiment in Rat Brain

Fig. 4 shows the measured signals at each step of signal retrieval during the *in vivo* rat brain experiment. The received signal at the receiving electrode is shown in Fig. 4 (a). As expected, the two transmission signals sent from μ-IBCOM1 and μ-IBCOM2 are superimposed at the receiving site. The FFT spectrum (Fig. 4 (b)) shows the frequency peaks at the modulation frequencies of both modulators. The two signals were separated by band-pass filters and then demodulated. The demodulated signals are shown in Fig. 4(c) and (d) corresponding to the signals from μ-IBCOM1 and μ-IBCOM2, respectively. Finally, the signals were fully retrieved by 5-bit digital-to-analog conversion. The retrieved signals are shown in Fig. 4(e) and (f), which are identical to the original neural signals stored in ROM shown previously in Fig. 3. The results show the successful separation and retrieval of IBCOM signals when the signals are sent from multiple transmitters simultaneously. The average bit error rate (BER) of the transmitted signals is measured as 10^{-5} with the maximum BER less than 10^{-3}.

We recorded neural signals in three periods: before applying IBCOM, during IBCOM, and after disconnecting IBCOM for more than 10 minutes per each session for 3 different rats. This experiment was repeated more than 10 times per rat. The limitation of 10 minutes was due to the limited capacity of the storing buffer in the DAQ-Card interfaced with the circuitry. Examples of the recorded signals are shown in Fig. 5. Neural firing signals during and after IBCOMs were observed unchanged as compared with those before applying IBCOM. We have not observed any artifacts or abnormal neural activities due to IBCOM. This indicates, qualitatively, that IBCOM does not affect neural activities. However, a more extensive study would be

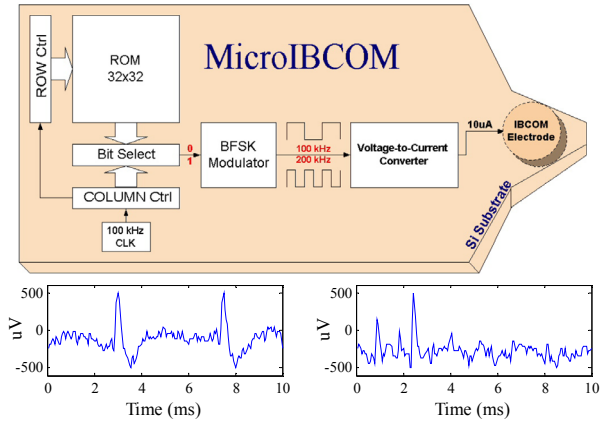

Fig. 3. Block Diagram of μ-IBCOM showing the major CMOS circuit blocks and the different neural signals stored in μ-IBCOM1 (left) and μ-IBCOM2 (right)

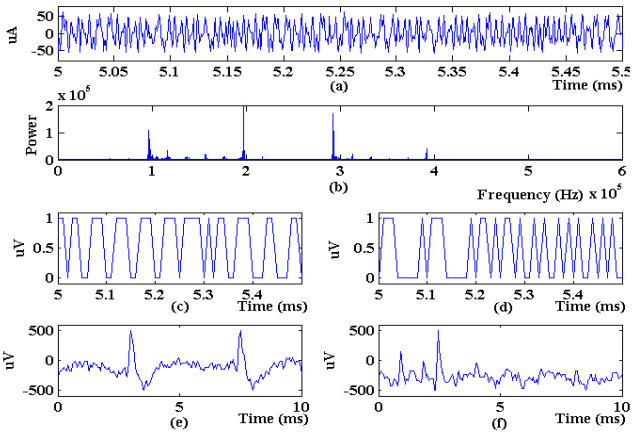

Fig. 4. Measured waveforms at each step of retrieval during the rat brain experiment: (a) Signal monitored at the receiving microelectrode (This is a superimposed signal of two output signals sent from μ-IBCOM1 and μ-IBCOM2), (b) FFT of the received signal showing four peaks at the corresponding modulated frequencies, (c) Demodulated signal after being separated by 100-200 kHz BPF, (d) Demodulated signal after being separated by 300-400 kHz BPF, (e) and (f) Fully-retrieved neural signals sent from μ-IBCOM1 and μ-IBCOM2 after 5-bit DAC of the signals shown in (c) and (d), respectively

necessary to fully determine the effects of IBCOM on neural firing.

The power required for sending the data through the brain has been tried with as low as 2 μAp-p for 100 kbps and 15 mm separation (limited by the rat brain) between the sending and receiving electrodes. In case of CMOS implementation, using 10 μA current, the transmitter power consumption is less than 65 μW using 2.5 supply voltage. This implies energy per bit of less than 650 pJ.

V. Conclusion

We have investigated Intra-Brain Communication (IBCOM) as a new method of sending neural signals through the brain. A series of experiments on rat brain has validated the concept and has demonstrated the feasibility of signal transmission from multiple sites to a receiver 15 mm away with a minimum transmission current below $2\mu A_{p\text{-}p}$. Neural signals have been recorded before, during and after IBCOM signal transmissions. We did not observe any noticeable affects on normal neural activities by transmitting IBCOM signals above 100 kHz after shaping and optimizing the transmitted signals. Two miniaturized IBCOM systems using different carrier frequencies were implemented in 0.25 μm CMOS process, and tested *in vivo* in rat brain. We successfully retrieved multiple neural signals simultaneously transmitted from different locations. We anticipate that IBCOM can open a new way for further miniaturization of next generation neural recording/stimulation systems as well as for reduction in power consumption of implanted microsystems.

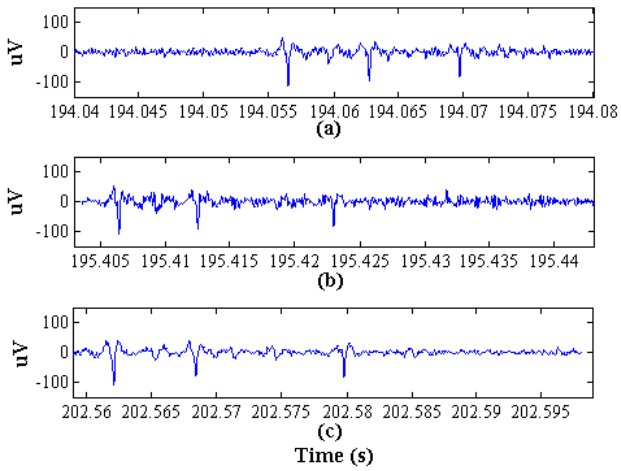

Fig. 5. Recorded neural signals from the same brain site (a) Before, (b) After, and (c) During IBCOM Application

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