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Baseband Signal Transmission Experiment for Intra-Brain Communication with Implantable Image Sensor

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***Abstract*— We demonstrate image signal transmission for wireless intra-brain communication. As a preliminary experiment, transmission characteristics of the brain phantom were measured. The baseband output signal from an implantable complementary metal-oxide-semiconductor (CMOS) image sensor is transmitted through the phantom. The image was successfully reproduced from the received signal.**

I. INTRODUCTION

Neural activities in the brain are of considerable interest to researchers in the fields of medicine and biology. Especially, we are interested in simultaneous multi-area imaging in order to observe cooperative activities between brain areas. An implantable complementary-metal-oxide (CMOS) image sensor is expected to be a solution. By the virtue of advanced CMOS technology, small image sensors have been designed and fabricated [1]–[5]. Such sensors are implantable even in a small mouse brain with low invasiveness. In previous works, neural activities in a mouse brain have been successfully observed by the sensors [5], [6] and can take images while the mouse is moving freely [4]. However, it is difficult to implant a lot of the sensors in the mouse brain because the number of wires is increased with the number of the sensors. In order to solve the problem, wireless communication techniques are required. We have proposed the distributed implantable image sensor system as shown in Fig. 1 [7]. In this method, signals are transmitted from image sensors to a receiver placed on a brain surface without any metal wires [8]. It is known that living tissues can be used as transmission media [9]–[13]. Thus, it could be possible to send images from implantable image sensors. An extracorporeal device is placed on the back of a mouse. The image data is sent from the sensor to the extracorporeal device through the brain.

In previous work, the signal modulated with image sensor output at a carrier frequency of 50 MHz was send through a brain and images were successfully received. If the baseband signal from the sensor can be directly transmitted, no modulation circuit is required for the implantable image sensor. Thus, it would be expected to be less invasive and more power efficient.

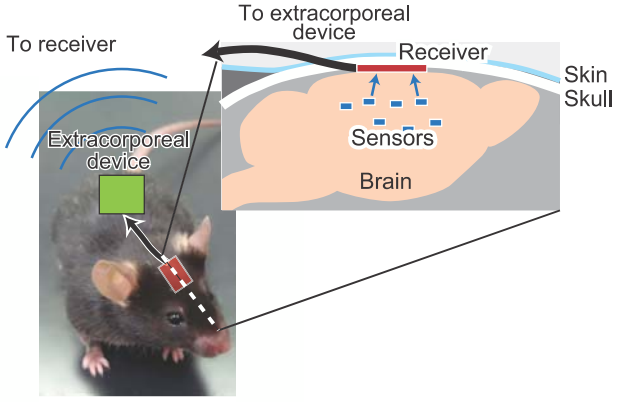

Fig. 1. Concept of distributed implantable CMOS image sensor system.

In this study, we demonstrate transmission of the baseband image sensor signal through a brain phantom. We measured transmission characteristics of a mouse brain at frequencies around the clock frequency of our image sensor and verified that it is possible to communicate through a mouse brain with miniature electrodes. The output signal from an implantable image sensor is transmitted through a brain phantom and the image are successfully reproduced from the received signal.

II. SIGNAL TRANSMISSION EXPERIMENT THROUGH BRAIN PHANTOM

By utilizing the conductive property of a brain tissue, it would be possible to transmit signals with low power consumption. In this work, we demonstrate the transmission of a signal from an image sensor without any metal wires. In order to verify the capability of wireless image transmission, a brain phantom is used. Because it is confirmed that the signal transmission characteristic of the phantom is similar to the real mouse brain, we used the phantom for primitive experiments in this work.

The brain phantom was prepared from phosphate-buffered saline mixed with 1% agar. The electrode used in the experiment is shown in Fig. 2. A 0.5 mm $\times$ 0.5 mm electrode for signal is placed on the front side. And, a 3.5 mm $\times$ 3.5

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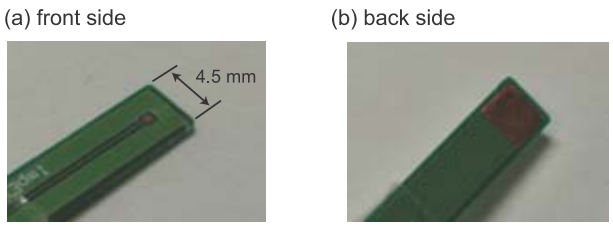

Fig. 2. Electrode for signal transmission.

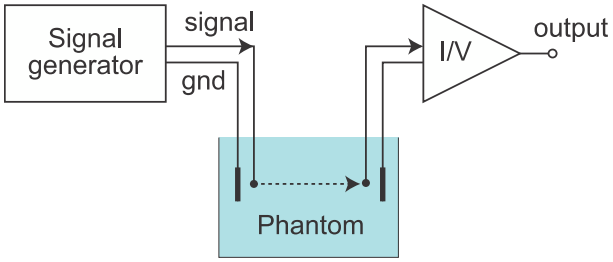

Fig. 3. Experimental setup for transmission characteristics measurement of brain phantom.

mm ground electrode is on the back side. Both of them are plated with Au and the isolation layer is made of glass epoxy.

Figure 3 shows the experimental setup for measurement of transmission characteristics. The electrodes are inserted into the brain phantom and placed opposite each other. A signal from the signal generator (Tektronics, AFG320) is input into the brain phantom. The received signal is converted from current to voltage by an I/V converter and the output signal is observed with an oscilloscope (Tektronics, MSO3014). The grounds of the equipments were isolated and only connected with the ground electrodes inserted in the phantom. In order to avoid accumulation of the parasitic capacity in the phantom, the signals are set to be bipolar.

Figure 4 shows the output signal amplitude as a function of the input signal amplitude. The spacing between the electrodes was 2 mm, and the frequency of the signal was set to 500 kHz. The solid line is a linear fit. The result indicates that the output is proportional to the input signal amplitude within the range of this experiment. The peak current for the signal with an amplitude of 1 V was approximately 4 mA. To avoid unwanted stimulation to the brain, the input signal level should be limited.

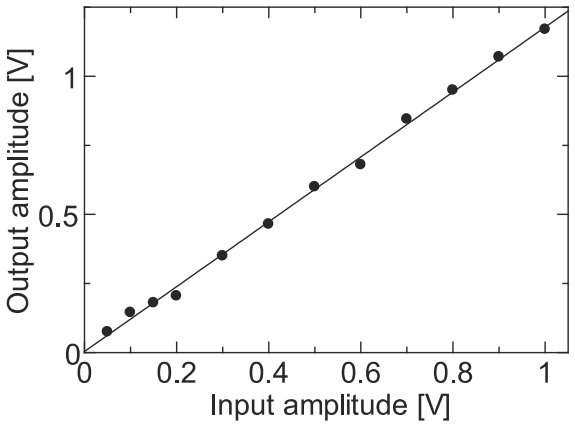

Fig. 4. Output signal amplitude as a function of input amplitude. The spacing between the electrodes was 2 mm, and the frequency of the signal was set to 500 kHz.

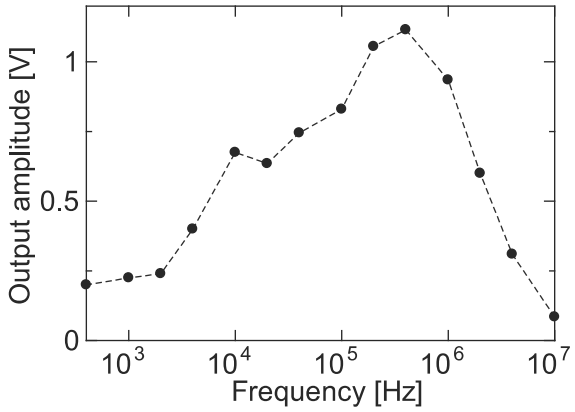

Fig. 5. Output signal amplitude as a function of frequency. The spacing between the electrodes was 2 mm, and the amplitude of the input signal was set to 0.5 V.

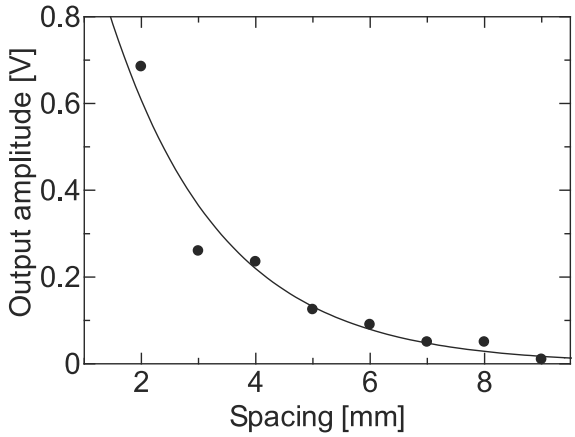

Fig. 6. Output signal amplitude as a function of spacing between the electrodes. The frequency was 500 kHz, and the amplitude of the input signal was set to 0.5 V.

Figure 5 shows the transmission spectrum. Here, the amplitude of the input signal was set to 0.5 V. The peak transmission is observed at approximately 5×10^5 Hz. At the frequencies lower than 10^4 Hz, the transmission efficiency is relatively low because of the capacitance of the phantom.

Figure 6 shows the output as a function of the spacing of the electrodes. The electrode spacing and the frequency were 2 mm, and 500 kHz, respectively. The solid line is a fitting line inversely proportional to the square of the spacing. Because the transmission efficiency decreases exponentially with the distance between the electrodes. this transmission method is especially suitable for an arrangement the sensor devices shown in Fig. 1 when the sensors are placed on the brain surface,

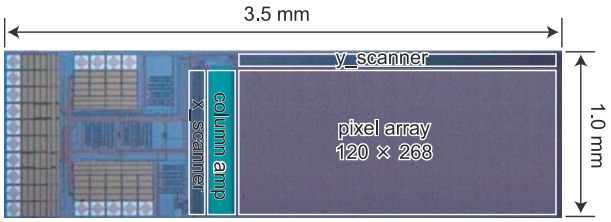

Fig. 7. Micrograph of an implantable image sensor.

TABLE I
SPECIFICATION OF IMAGE SENSOR FOR IN-VIVO IMAGING [6]

Technology		0.35 μm 2-poly 4-metal standard CMOS process
Supply voltage		3.3 V
Chip size		1.0 mm × 3.5 mm
Pixel	Type	3-transistor active pixel sensor
	Size	7.5 μm × 7.5 μm
Array size		120 × 268
Photodiode type		Nwell-Psub
Fill factor (%)		30

III. DEMONSTRATION OF IMAGE SIGNAL TRANSMISSION THROUGH BRAIN PHANTOM

Based on the result in the previous section, we demonstrate transmission experiment of an image sensor signal through the brain phantom. In this experiment, the image sensor is the same as the CMOS image sensor used for *in-vivo* neural activity imaging of a mouse brain in our previous work [6]. The micrograph and specification of the sensor are shown in Fig 7 and Table I, respectively.

The schematic diagram of the experimental setup is shown in Fig. 8. A resolution test chart is used as an observation target. The output signal from the image sensor through the control board was input into the phantom with the electrode shown in Fig. 2. As in the experiment in the previous section, the distance between the electrodes was 2 mm. The received signal was converted and amplified by the I/V converter and captured by the oscilloscope. The clock for the image sensor was set to 500 kHz. It corresponds to the frame rate of 7.8 frames per second.

Figures 9 show typical measured waveforms. Here, each waveform corresponds to 4 rows of an image from the sensor. The waveform of the signal through the phantom (Fig. 9(b)) is noisy compared with that of the signal just after the sensor (Fig. 9(a)). Relatively high frequency noise received by the wires and the phantom can be reduced by choosing the operation clock of the sensor and applying image processing. The low frequency distortion is due to the poor transmission efficiency of the phantom. It would be overcome by modulating the output signal.

Figures 10 show examples of images from the sensor. Figure 10(a) is the reconstructed image from direct output signal. The result through the brain phantom is shown in Fig. 10(b). For this image, an image filter is applied in order to reject high frequency noise. As a result, the test

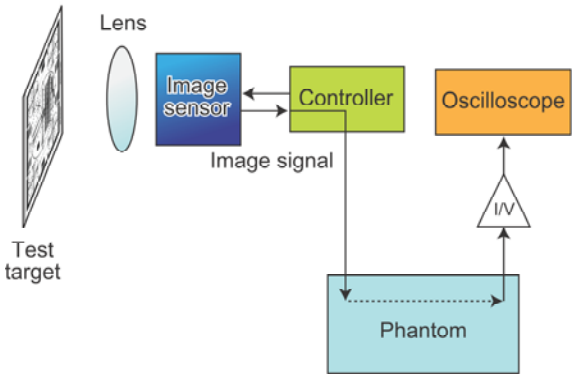

Fig. 8. Experimental setup of image transmission

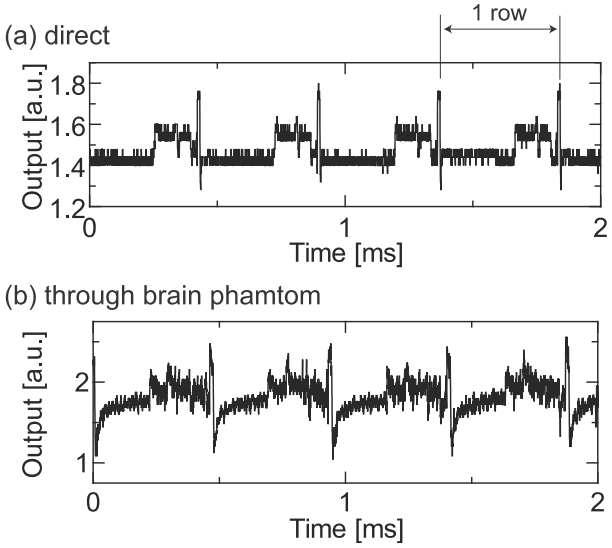

Fig. 9. Waveforms of the image sensor signal.

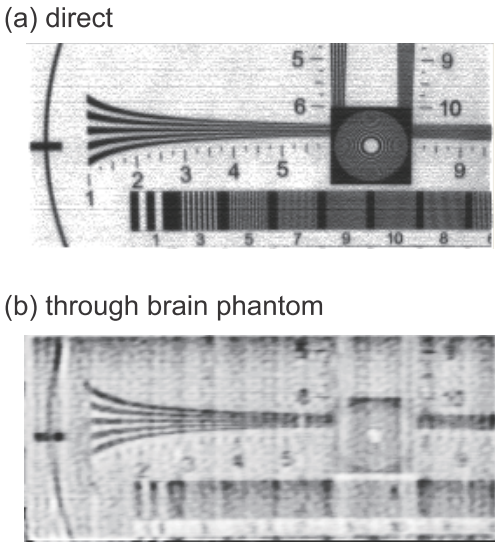

Fig. 10. Recunstructed images from the signals transmitted (a) directly and (b) through the brain phantom.

target pattern is successfully obtained even after transmission through the phantom although the detail of the pattern was lost. In addition, artifacts appeared on flat area due to the loss of low spatial frequency components. Another problem is the effect of the current to the brain activity. In order to reduce it, the current has to be as low as possible. Al-Ashmouny *et al.* have reported that no effect was observed with the current of 2 $\mu A_{p.p.}$ [13]. However, it should be verified carefully. These problems would be solved by digitizing or changing modulation method of output signal.

IV. Conclusion

We proposed to transmit the image signals of implantable image sensors through a mouse brain for multi-area neural activity imaging. As a preliminary experiment, transmission characteristics of the brain phantom were measured. We also demonstrated image signal transmission through the phantom. This method is very simple and expected to be low power consumption. Further improvement would be realized by optimization of output signal modulation.

Acknowledgements

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