Implantable micro-sized image sensor for data transmission with intra-vital optical communication

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Published in *The Journal of Engineering*; Received on 1st November 2016; Accepted on 14th November 2016

Abstract: Interest in implantable microchips for medical sensors is increasing. To reduce the invasiveness of implantation, wireless data transmission in a living body is an important issue shared by all such sensors. Here, the authors report on a light-based wireless data transmission method for implantable biomedical sensor chips. An implantable micro-sized image sensor ($400 \times 1200\ \mu m^2$) that was designed to modulate a small light-emitting diode ($\lambda = 855$ nm) with pulse-width modulation for intra-vital optical communication (IOC) was developed. Both a transmitter device and a receiver device for IOC were prepared, and optical image data transmission through biological tissue (a mouse skull bone) was successfully demonstrated.

1 Introduction

Recent advances in implantable microchips based on semiconductor technology for physiological monitoring from inside the body are becoming an increasing interest in both fundamental research [1] and medical applications [2]. Complementary–metal–oxide semiconductor (CMOS) technology enables the integration of a variety of functions such as physiological data acquisition, processing, and analysis on a single chip. Thus, the CMOS-based implantable microchip technology is attractive for physiological monitoring inside the body for medical use [3, 4]. To reduce the invasiveness of the implantation, wireless data transmission from implanted sensors to the outside of the body is an essential issue shared by all such implantable medical sensors. A wired connection between the implanted sensors and outside devices raises the risk of traumatic injury and bacterial infections and reduces the quality of life of patients [5]. Although wireless communication technology using radiofrequency (RF) has been well developed, wireless RF telemetry limits the miniaturisation of implantable devices because of the necessity for large antennas.

In a previously report, we proposed the application of intra-body communication (IBC) to implantable medical sensors as a wireless data transmission method [6, 7]. IBC utilises biological tissues as a conductive medium to transmit small current of electrical signals. Thus, it is considered a good choice to communicate between multiple implanted chips, as shown in Fig. 1*a*. However, such a data transmission approach using electric current can only be applied in a conductive medium. Signal transmission via body parts that have relatively high impedance (e.g. skull bone and skin) is limited. Therefore, to realise a communication system between implanted medical sensors and the outside of the body, other approaches that enable the transmission of signals via non-conductive media should be applied.

In this paper, we report on a light-based data transmission method inside the body, called intra-vital optical communication (IOC), by using an implantable image sensor and a micro-light-emitting diode (micro-LED), as illustrated in Fig. 1*b*. We describe the implantable image sensor, which was designed to modulate the micro-LED to optically transmit image data. Then, both a transmitter device and a receiver device were prepared and image data transmission with IOC via the skull bone as a non-conductive medium was demonstrated.

2 Design and fabrication of the implantable micro-sized image sensor

The implantable micro-sized image sensor was fabricated using 0.35-µm 2-poly, 4-metal standard CMOS technology. Figs. 2*a* and *b* show photographs of the fabricated implantable image sensor, which has a width, length, and thickness of 400, 1200, and 125 µm, respectively. As shown in Fig. 2*b*, the implantable image sensor has only three bonding pads, two input pads (VDD and GND) for power-supply, and one output pad (OUT) for modulation of a micro-LED to transmit image-data with light. Fig. 2*c* shows a block diagram of the image sensor. The block diagram is composed of three parts: an image-sensing circuitry, internal bias and signal generator circuitry, and pulse-width modulation (PWM) modulator circuitry. The image-sensing circuitry has 30×90 pixels (pixel size: $7.5 \times 7.5\ \mu m^2$) and vertical and horizontal scanners. The internal bias circuitry supplies a bias voltage (V_{BIAS}) and constant current (I_{BIAS}). The relaxation oscillator generates triangle waves from I_{BIAS} and a clock signal (CLK). The frequency of the internally generated clock signal is 1.1 kHz. The PWM modulator circuitry translates the pixel value to the PWM output signal by comparing of the pixel output voltage with the internally generated triangle wave.

3 Evaluation of the implantable micro-sized image sensor

The sensitivity of the implantable image sensor was evaluated. The sensor was operated with a 2.5-V supply voltage. Fig. 3 shows sensitivity of the implantable image sensor. Depending on the incident light intensity from 0 to 40 nW/cm^2 ($\lambda = 635$ nm), the output pulse widths were linearly changed. The pixels were gradually saturated in the incident light intensity of over 40 nW/cm^2. The dynamic range of the image sensor was improved compared with the previously reported implantable image sensor for IBC [7].

4 Transmitter and receiver for intra-vital optical communication

Fig. 4*a* shows a schematic of the experimental setup for image data transmission with IOC via biological tissues. To transmit image data with light, a micro-sized near-infrared light-emitting diode (NIR-LED) of width, length, and thickness of 250, 250, and 170 µm, respectively ($\lambda = 855$ nm, ES-SASFPN10, Epistar Corp., Taiwan)

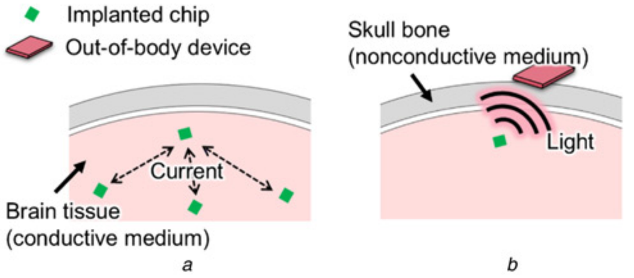

Fig. 1 *Schematics of communication between implanted devices*
a IBC
b IOC

was modulated with PWM output from the implantable image sensor with an analogue switch (AD841, Analog Devices Inc., Norwood, MA, USA). Modulated light was received by a compact Si-photodiode (PD) (HPI-12N, KODENSHI Corp. Kyoto, Japan). The received photocurrent signals were converted to voltage by an *I–V* converter, amplified by non-inverting amplifier circuitry, and obtained by an oscilloscope (DPO4043, Tektronix Company, Tokyo, Japan). Received optical signals were converted to pixel values and were reconstructed into a single two-dimensional image by using original software on MATLAB (Mathworks Inc., Natick, MA, USA).

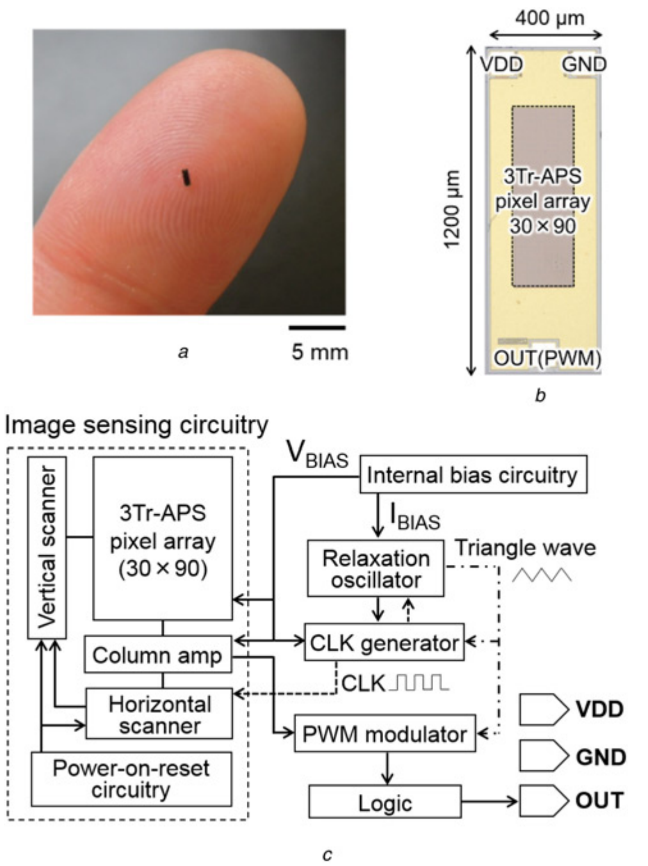

Fig. 2 *Implantable micro-sized image sensor for IOC*
a Photograph of the image sensor for IOC
b Microscopic image of the sensor. The sensor chip was 400 μm wide, 1200 μm long and 125 μm thick
c System block diagram of the sensor. The sensor had two inputs (VDD, GND) and one output (OUT)

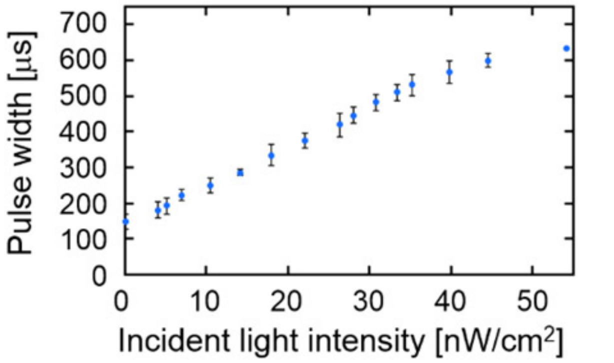

Fig. 3 *Sensitivity of implantable micro-sized image sensor for IOC. Pulse width of PWM out as a function of incident light intensity. Error bars show standard deviations that were derived from distribution of pixels*

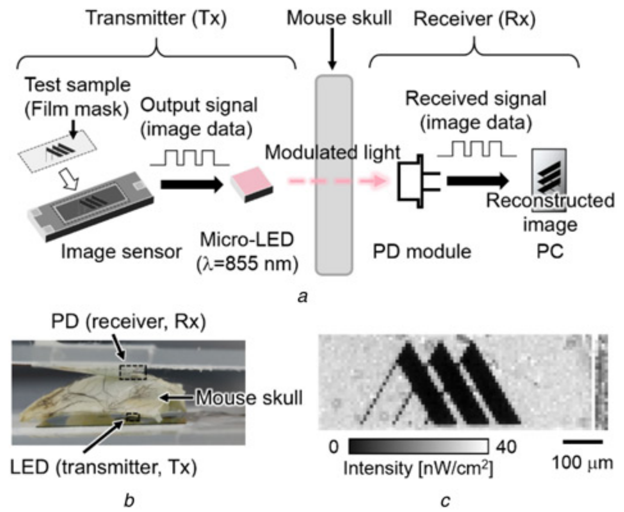

Fig. 4 *Image data transmission with IOC*
a Schematic of experimental setup for image data transmission
b Photograph of experimental setup with a mouse skull
c Transferred image of 'NAIST mark' pattern

5 Image data transmission via biological tissue

Finally, we demonstrated image data transmission with IOC via a mouse skull bone. All animal care and treatment protocols were approved by the Animal Experiment Committee of the Nara Institute of Science and Technology. Fig. 4*b* shows a photograph of the experimental setup. A film mask was placed onto the image sensor as a test sample. Modulated LED light was transferred through a mouse skull bone of ∼200 μm in thickness and received by the receiving PD module. Fig. 4*c* shows a representative image that was obtained by the implantable image sensor and transferred with IOC via the mouse skull. The image of the film mask pattern 'NAIST mark' was successfully transferred with IOC and reconstructed. In this research, image data transmission rate was 0.35 fps (2700 pixels/frame). This low data transmission rate was determined by the original frame rate of the implantable image sensor. Considering the previous reports, high-speed optical data transmission (up to ∼100 Mbps) was transcutaneously demonstrated using porcine skin [8, 9]. Thus, IOC has the potential to be applied to high-speed data transmission for biomedical applications.

6 Conclusion

We developed IOC by using an implantable micro-sized image sensor and a micro-sized NIR-LED. A specially designed image sensor was fabricated, and its sensitivity was evaluated. We demonstrated image data transmission with IOC through mouse skull bone as a nonconductive biological tissue. A wireless data transmission technique using light is a promising approach to relay important signals obtained by implanted biomedical sensors to the outside of the body, especially through nonconductive body parts. The combined use of IBC and IOC will fulfil the requirements for realising a communication system for miniaturised implantable medical sensors.

7 Acknowledgments

This research was supported by Tateishi Science and Technology Foundation (2151020), Grants-in-Aid for Scientific Research (26249051 and 15K21164) from Japan Society for the Promotion of Science (JSPS) of Japan, Humanophilic Innovation Project, and VLSI Design and Education Center (VDEC), The University of Tokyo, in collaboration with Cadence Corporation and Mentor Graphics Corporation.

8 References

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