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Photo-sensing Resolution of Unwired-communication Chip in Inhomogeneous RF-magnetic Field

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1. Introduction

There is an increasing concern about biological assay in the fields of personalized medicine, food-security control, and environmental monitoring. Recently, there's been an increase in research into bioluminometry which has the potential to realize compact and inexpensive measuring apparatus [1]. Fig. 1 illustrates a practical example of a wireless biosensing system applying bioluminometry [2]. Since the sensor chip in this system must function in a sample solution, a suitable means of transmitting power and sensing data is by using RF communication [3]. The signal intensity of luminometry is very weak, so resolution of the sensing characteristics should be clarified for the sensor chip. In this paper, we evaluated the photo-sensing resolution of the unwired-communication chip powered by an inhomogeneous RF-magnetic field.

2. Experimental and Results

System configuration

To demonstrate the system, we fabricated a prototype shown in Fig. 2. The photographs show an R/W coil with 40 turns on a printed circuit board and the sensor chip with a volume of 2.5 x 2.5 x 0.5 mm^3. The chip monolithically integrates an RF front-end circuit which operates at a carrier frequency of 13.56 MHz, a control logic circuit, a sensor analog circuit, and a photosensor. The photosensor consists of two photodiodes (PDs) , one for a signal (PDsig) and the other for a reference (PDref). The PDref measures the background containing dark current and common-mode noise due to supply-voltage fluctuation by shielding its sensing area. These PDs are operated in a charge-integration mode, so the captured number of photons is converted to the change in cathode voltage. The difference between cathode voltage changes of PDsig and PDref is amplified and converted to a digital value by an 11-bit (2048) ADC with a $\Delta\Sigma$ modulator. Circuit activation/inactivation and parameter setting (amplifier gain and current source) are controlled by the custom commands from the PC through the R/W unit. Power transfer from the R/W coil is accomplished by the RF circuit through the coil on chip.

The RF-magnetic-field distribution around the R/W coil

Fig. 3 illustrates the RF-magnetic-field distribution along the Z axis on an X-Y plane, which is 0.5 mm above the R/W coil. The RF-magnetic field was evaluated from an induced voltage on a probe coil with a single loop. The coordinate origin corresponds to the center of the R/W coil. The RF-magnetic field indicated a remarkable change on the X-Y plane. The maximum intensity was 379 A/m at the center. It decreased with a radial distance from center (r), and fell significantly in the region between r=2.5 mm and 3.5 mm where the coil wiring was placed.

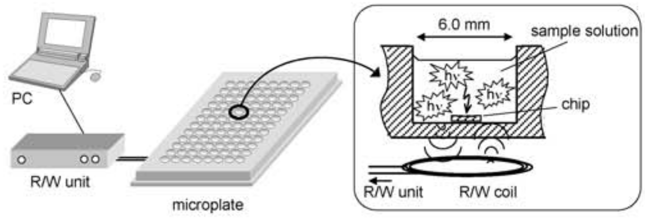


Fig. 1: Schematic of wireless biosensing system.

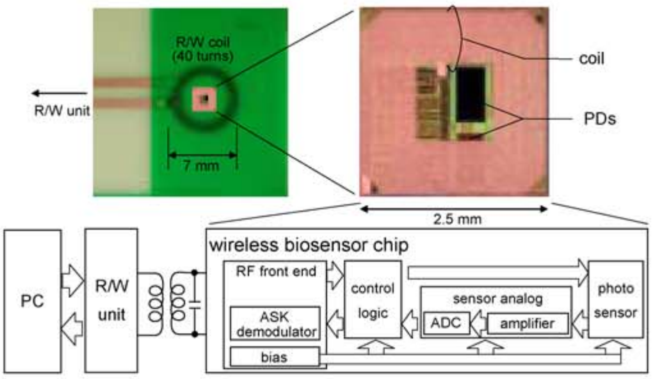
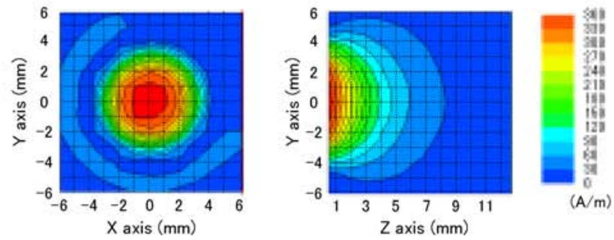


Fig. 2: Photographs and block diagram of wireless biosensing system.



(a) X−Y plane (Z=0.5 mm) (b) Y−Z plane (X=0 mm)

Fig. 3: Z component of RF-magnetic field around R/W coil.

The chip position dependence of PDs output

To evaluate an effect of the positional variation in the RF-magnetic field on the photo-sensing characteristics, the sensor output was measured at various positions on the R/W coil. In this measurement, an LED was fixed above the sensor chip and irradiated the sensor chip with a light of constant intensity. Fig. 4 plots the positional dependence of the ADC output transmitted from the sensor chip. The signal integration time was set to 100 ms and amplifier gain was set to 100. The "H" indicates the ADC output when the LED is turned on and the "L" indicates the output when the LED is turned off. When the LED was turned on from the off state, the ADC output rose as the number of incident photons increased. The magnitude distribution of the RF-magnetic field in Fig. 3 was redrawn in Fig. 4. Communication failed in the region |X|>3 mm where the magnitude was lower than 160 A/m, which corresponded to the lower limit for chip operation. Although each variation of the ADC outputs ("L" and "H") was almost 170 in the communication area, they behaved in the same manner to the RF-magnetic field. The difference between "L" and "H" (denoted as "H-L" in Fig. 4) stayed in the variation of 4. Thus, the resolution of the photosensor was about ±30 μV, since the ADC output was expressed in 11 bits (2048) for the input range of ±1.5 V. This shows our wireless biosensor chip had good resolution comparable to a high-resolution detector driven by a stabilized power source.

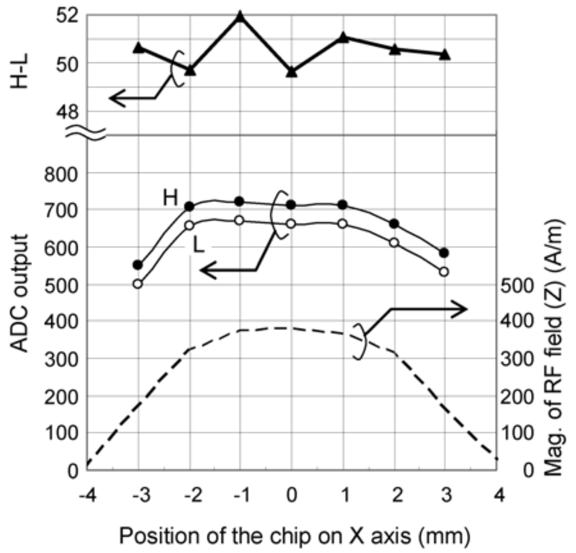


Fig. 4: Relationship between chip position and ADC output.

The demonstration of bioluminescence measurement

To demonstrate the resolution of photo sensing, a bioluminometric quantification of adenosine triphosphate (ATP) was carried out. The bioluminescence reaction is as follows.

$$ATP + luciferin + O_2 \xrightarrow{luciferase} AMP + PPi + oxyluciferin + CO_2 + h\nu \quad (1)$$

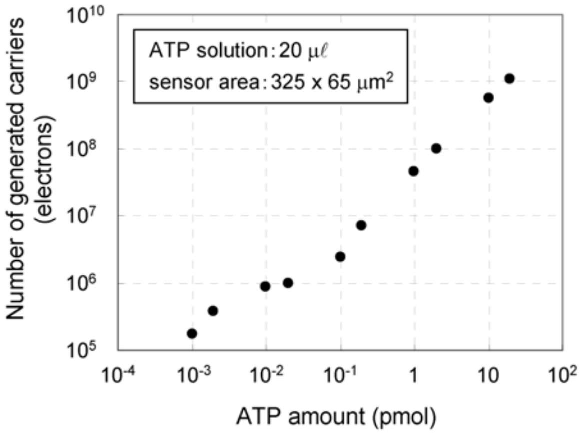


Fig. 5: Relationship between ATP amount and generated carriers.

According to this reaction, the amount of ATP can be quantified by measuring bioluminescence intensity. Bioluminescence was observed by the photosensor chip placed in the reaction cell. Fig. 5 shows the relationship between ATP amount and the number of detected electrons. The numbers of electrons were calculated from ADC outputs. An almost linear relationship between the ATP amount and sensor response was obtained.

3. Conclusions

We developed the wireless biosensing system and evaluated photo-sensing characteristics. Though the RF-magnetic field of the R/W coil had a significant positional variation, stable sensing data was obtained in the region where the magnitude was larger than 160 A/m. The photo-sensing resolution was shown to be ±30 μV even in the inhomogeneous RF-magnetic field. We also demonstrated bioluminometric reaction by quantifying ATP amount. We observed good linearity between ATP amount and ADC output on bioluminescence with a resolution of 1 fmol ATP.

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