BRIEF PAPER Special Section on Analog Circuits and Their Application Technologies

A 385 × 385 μm^2 0.165 V 0.27 nW Fully-Integrated Supply-Modulated OOK Transmitter in 65 nm CMOS for Glasses-Free, Self-Powered, and Fuel-Cell-Embedded Continuous Glucose Monitoring Contact Lens

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SUMMARY This work presents the lowest power consumption sub-mm^2 supply-modulated OOK transmitter for self-powering a continuous glucose monitoring (CGM) contact lens. By combining the transmitter with a glucose fuel cell that functions as both the power source and a sensing transducer, a self-powered CGM contact lens was developed. The 385×385 μm^2 test chip implemented in 65-nm standard CMOS technology operates at 270 pW with a supply voltage of 0.165 V. Self-powered operation of the transmitter using a 2 × 2 mm^2 solid-state glucose fuel cell was thus demonstrated.

key words: *continuous glucose monitoring, smart contact lens, low-power, wireless transmitter, glucose fuel cell*

1. Introduction

The prevalence of diabetes worldwide continues to increase year by year. Continuous glucose monitoring of diabetics and those at risk for developing diabetes is very important [1], [2]. However, existing needle-type glucose monitoring systems are painful [3]. One of the promising candidates for needle-less pain-free glucose monitoring is a continuous glucose monitoring (CGM) contact lens [4]. Because tear glucose level has a high correlation with blood glucose level, it has the potential to be a de facto standard for continuous glucose monitoring.

Existing continuous glucose monitoring contact lenses are based on RFID technology that work with dedicated smart glasses [4]. This approach has a fatal problem from the viewpoint of usability and high cost.

In order to solve these issues, we propose built-in energy harvesting from tear glucose in CGM contact lenses. Tear glucose is one of the most stable energy sources secreted by the human body. Furthermore, by using a selective glucose fuel cell, glucose energy can be utilized not only as an energy source but also as a sensing transducer for glucose concentration.

Recent progress in the field of biofuel cells has enabled the fabrication of glucose fuel cells on silicon wafer [5]. Glucose fuel cells are capable of producing an output of

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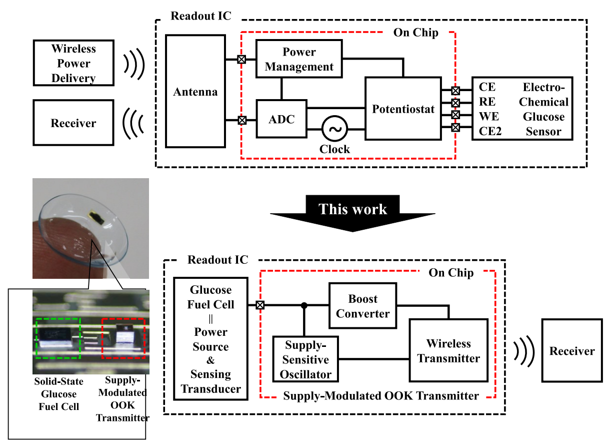


Fig. 1 Conceptual diagram of this work compared to previous continuous glucose monitoring contact lens and microphotograph of the prototype.

2.3 μW/cm^2 and an open-circuit voltage of 0.55 V, which can be sustained for more than 48 hours. We have developed 0.6 mm×0.6 mm CMOS-compatible solid-state glucose fuel cell with 370 mV OCV and 0.27 μW/cm^2 power density at a 30 mM glucose concentration [6]. The output voltage of the glucose fuel cell correlates with the glucose concentration. This makes it possible for the fuel cell to act as both the power source and sensor. By measuring the fuel cell output voltage, we can detect the blood glucose concentration in the user's body.

Figure 1 shows the schematic of this work and a microphotograph of the prototype CGM contact lens. Conventional RFID-based glucose monitoring requires a 3 μW 0.36 mm^2 footprint chip, a 1 cm diameter off-chip antenna, and an off-chip electrochemical glucose sensor [4]. Its power consumption is mainly due to the use of an electrochemical sensing frontend. The electrochemical sensor must be embedded with a potentiostat for biasing the electrodes. The accuracy of the sensor is dependent on accurate DC biasing. Thus, a stable power supply is essential for this architecture. In addition, wireless power delivery utilizing AC and AC-to-DC conversion is required, resulting in a large footprint.

On the other hand, our architecture using supply-modulated on-off keying (OOK) transmitter and biofuel cell does not require a potentiostat because the biofuel cell generates DC voltage. Moreover, the device does not need the large off-chip components and wireless power delivery. Therefore, the device power consumption can be reduced dramatically to nW-order, supplied by a small-footprint glucose fuel cell. A self-powered and small area CGM is achieved as shown in the microphotograph of the prototype CGM contact lens in Fig. 1.

This work presents the world's lowest power sub-mm^2 fully-integrated OOK CMOS transmitter, that enables a glasses-free and self-powered continuous glucose monitoring contact lens. We demonstrate a performance improvement compared to a previously reported fuel cell embedded CGM contact lens [7]. Our architecture reduces the input voltage and the power consumption, enabling self-powered operation with a smaller-footprint glucose fuel cell at a lower glucose concentration. The low input voltage not only reduces the power consumption of the circuit but also increases the output current of the glucose fuel cell. The output current of the glucose fuel cell takes a local maximum value when the input voltage is approximately 100 mV [6]. The measurement results of our prototype test chip in 65 nm CMOS fabrication showed 0.27 nW power consumption at 0.165 V supply voltage. We also demonstrate a functional test and self-powered wireless transmission with an integrated $2 \times 2\,\text{mm}^2$ solid-state glucose fuel cell.

The remainder of this paper is organized as follows. Section 2 introduces the proposed fully-integrated supply-modulated OOK transmitter for self-powered glasses-free continuous glucose monitoring contact lens. Section 3 describes the circuit implementation and measurement setup. Section 4 summarizes the measured results. Section 5 demonstrates the self-powered operation with a glucose fuel cell. Section 6 presents the conclusions of this study.

2. Fully-Integrated OOK TX for Self-Powered Continuous Glucose Monitoring Contact Lens

2.1 Product Concept

Figure 2 shows the conceptual block diagram of this work. The object of this study is a self-powered glasses-free continuous glucose monitoring contact lens. The prototyped module consists of two parts: one is a supply-modulated OOK CMOS transmitter and the other is a solid-state glucose fuel cell that functions as both the power source and the glucose concentration transducer from the tear. Increasing glucose concentration results in increasing the output voltage of the fuel cell. This also increases the operating frequency of a self-oscillating voltage doubler [8]. The transmission rate which is determined from the divided output of the self-oscillating voltage doubler also increases. This relationship is effective even in lower glucose concentrations. Therefore, the glucose fuel cell also senses the glucose concentration. The proposed glucose sensor just detects the relative glucose concentration to previous monitored values. However, if the glucose concentration as a function of transmission period has monotonicity, the absolute value can be

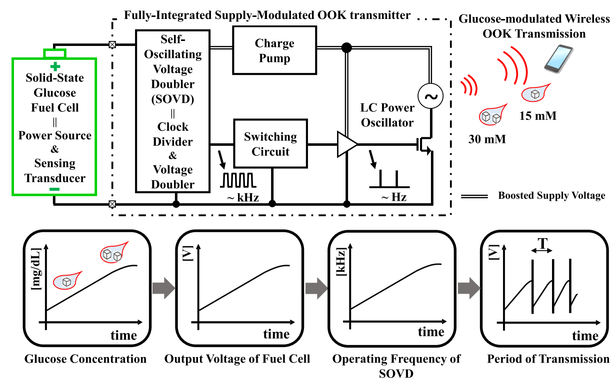


Fig. 2 Proposed glucose sensing and supply-modulated OOK transmitter.

determined by calibration.

This architecture eliminates the requirement of the electrochemical sensor circuit; therefore, the circuit is simplified and can operate with extremely low power consumption. Hence, the external power supply which requires a large area, as in a previous report [4] can also be removed. The smaller overall area of the device also increases the user's comfort. Further, our device consists of a transmitter requiring no off-chip components. Moreover, the glucose fuel cell can be fabricated using CMOS-compatible process, allowing the device to be produced at a low cost. The two components are mounted on the flexible PCB board, electrically connected by wire bonding, and covered by insulating resin.

As a sensing transducer, the glucose fuel cell output is designed to be anode-limited. The output voltage of the glucose fuel cell increases with the glucose concentration. By combining the glucose fuel cell with a supply-modulated OOK transmitter, the glucose concentration can be sent to the receiver. The output power of the glucose fuel cell increases with an increase in the temperature; however, it decreases as the resistance value increases when the temperature is too high. However, because the surface temperature of the eye is almost constant, the temperature variations of the glucose fuel cell can be ignored. Similarly, it is not necessary to consider the temperature variations of the transmitter. If a high precision measurement is required, it is necessary to add a supply-insensitive temperature sensor which provides a pulse width modulation (PWM) output [9].

2.2 Circuit Implementation

Figure 3 shows the circuit diagram of the proposed OOK transmitter. The transmitter consists of four parts: a self-oscillating voltage doubler [8], Dickson charge pump, switching circuit, and LC power oscillator. We focus on low power and small area wireless transmission to operate with the small fuel cell. For low power consumption, the transmitter operates at low frequency under subthreshold voltage. The self-oscillating voltage doubler oscillates around 1 kHz. Because an LC power oscillator consumes large power, the transmitter boosts the input voltage slowly and transmits at a

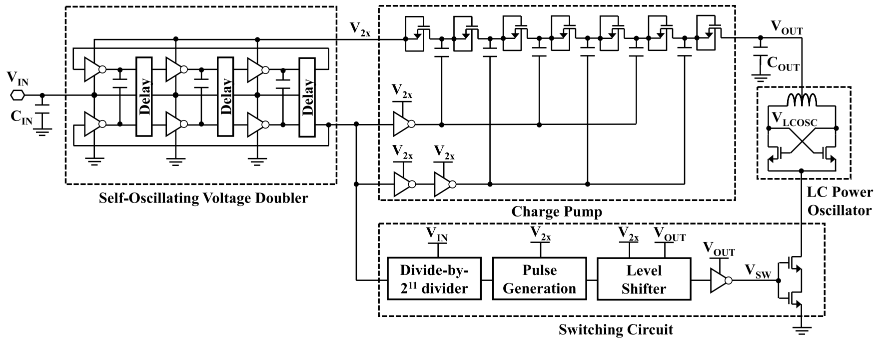


Fig. 3 Circuit diagram of the proposed OOK transmitter.

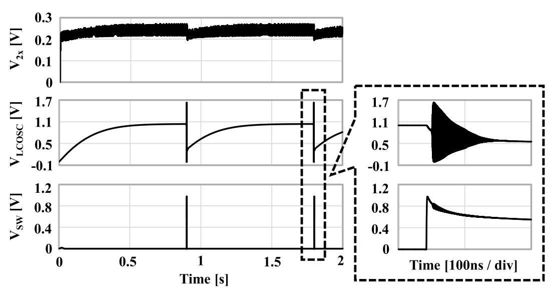


Fig. 4 Simulated waveforms of the proposed OOK transmitter when the input voltage is 170 mV.

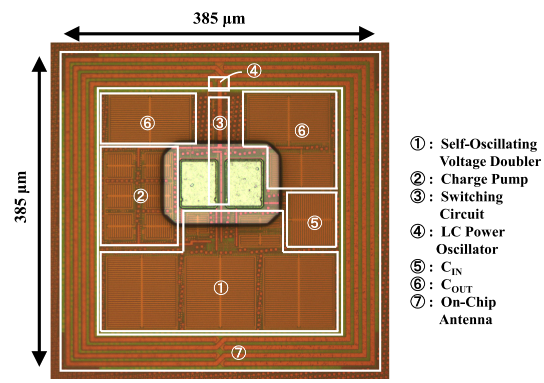


Fig. 5 Chip microphotograph.

long period. The LC power oscillator is activated at approximately 1 Hz, which is divided by the 2^{11} switching circuit. A divide-by-2^{11} divider is a series of 11 of divide-by-2 dividers consisting of flip-flops and logic gates. The self-oscillating voltage doubler and Dickson charge pump are adopted as a boost converter. This enables low power boost conversion from a low input voltage without off-chip components or special process characteristic such as deep-trench capacitors (250 fF/μm^2) [10]. They are utilized to achieve low power consumption, sacrificing conversion efficiency. A standard inverter using one NMOS transistor and one PMOS transistor was utilized for low-voltage operation.

The supply voltages of each circuit components were optimized for minimizing the power consumption. Power consumption was minimized by the leakage-reduction switching circuit. The most critical part from the viewpoint of power consumption is the LC power oscillator. Thus, we implemented stacked NMOS transistors to minimize leakage current. To achieve sufficient current of oscillation of the LC oscillator while minimizing the size of stacked NMOS transistors, we used a level shifter [11]. Switching the LC oscillation using the level shifter can reduce the quiescent power and can shorten the starting time of the LC oscillation owing to the high slew rate so that the output capacitance (C_{OUT}) can be reduced.

2.3 SPICE Simulation

To verify the effectiveness of our approach, SPICE simulation was conducted using standard 65 nm CMOS technology. Figure 4 shows the simulated waveforms of the proposed OOK transmitter when the input voltage is 170 mV. Owing to the limitation in our simulation environment, the right-part inset simulation results enclosed by the dotted line were separately simulated. The self-oscillating voltage doubler generates almost twice the input voltage. The Dickson charge pump boosts the voltage further to operate the LC power oscillator and transmitter. LC oscillation by the switching circuit was successfully confirmed. In the simulation, the proposed OOK transmitter operates with the supply voltages from 150 mV to 380 mV.

3. Test-Chip Design and Measurement Setup

A prototype test chip was fabricated using standard 65 nm CMOS technology without any special high-density capacitors [10]. Figure 5 shows the microphotograph of the test chip. The occupied footprint including the on-chip antenna of the transmitter is $385 \times 385\,\mu m^2$, which is smaller than the corresponding chip on a CGM contact lens previously reported [4]. Inductance and capacitances constitute a large area of the chip. In particular, C_{OUT} is large for the stability of the start-up of the LC power oscillator and the longer time of the oscillation. The on-chip antenna also occupies a large area for a higher Q-value and a longer communication distance.

Figure 6 shows the measurement setup. A manual probing technique was used for supplying power (alpha 150, Apollowave Corp.). A source measure unit (SMU) was utilized for accurate power and voltage measurement.

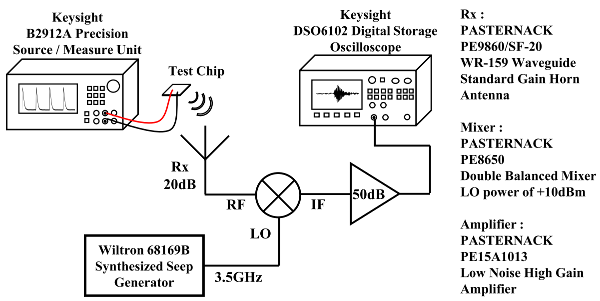


Fig. 6 Measurement setup for functional verification of the test chip.

The communication distance from the chip surface of the transmitter to the center of the receiver antenna was longer than 10 cm. The communication distance can be extended by adopting an off-chip antenna, which can be implemented on the fringe part of the contact lens [4].

4. Measurement Results

Figure 7 (a) shows the measured waveform of wireless transmission. The wireless transmission waveform was observed from 0.165 V to 0.39 V. Since the pulse width of the activating LC power oscillator decreases with increasing supply voltage, a higher supply voltage results in no oscillation. This is the reason why wireless transmission at supply voltages above 0.39 V was not observed. It is presumed that the difference between the measured and simulated results of the operating voltage range is caused by the effect of parasitic components.

Figure 7 (b) shows the time period of the measured power consumption obtained from the SMU. Wireless transmission can be detected down to a supply voltage of 0.165 V with a minimum average power consumption of 270 pW. The period of the peak power consumption points to the increasing LC oscillation as the input voltage increases. Fluctuations of the peak points at higher voltage conditions are assumed to be due to the limited time resolution of the SMU. Also, as the operating temperature rises, the power consumption increases.

Figure 8 shows the measured period of wireless transmission and the power consumption as a function of the input supply voltage. Since the period is shown to depend on the input supply voltage, supply-modulated OOK transmission is successfully verified. Therefore, by connecting the transmitter to the glucose fuel cell, glucose concentration can be detected. The power consumption is low enough for the small fuel cell to drive the transmitter.

Table 1 shows a performance comparison among small form factor CMOS transmitters [4], [7], [10], [12]. Our proposed architecture outperforms the others in terms of power consumption and operating range of supply voltage. One of the most important factors in achieving low power consumption is the introduction of an energy-efficient level shifter that reduces the leakage current from the LC power oscillator. The widest operating voltage range among the sub-mm^2 transmitters has been achieved. This is beneficial for biosensing applications that require a wide dynamic range.

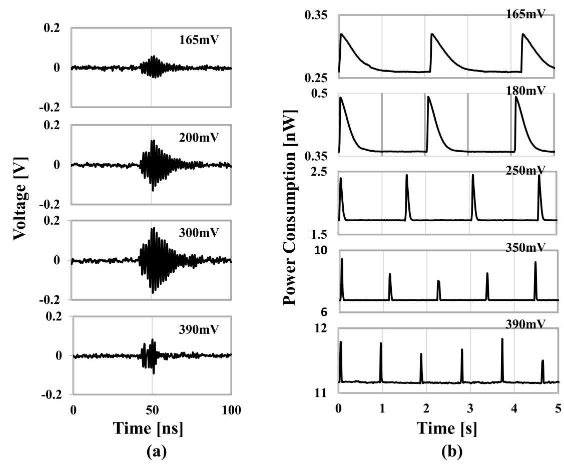


Fig. 7 Measured results: (a) waveforms of transmission by using oscilloscope (b) power consumption obtained from SMU.

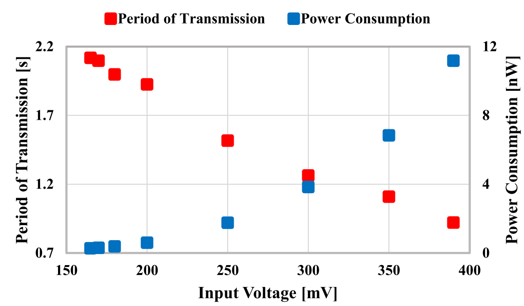


Fig. 8 Measured results of the period of wireless transmission and power consumption dependence on input supply voltage.

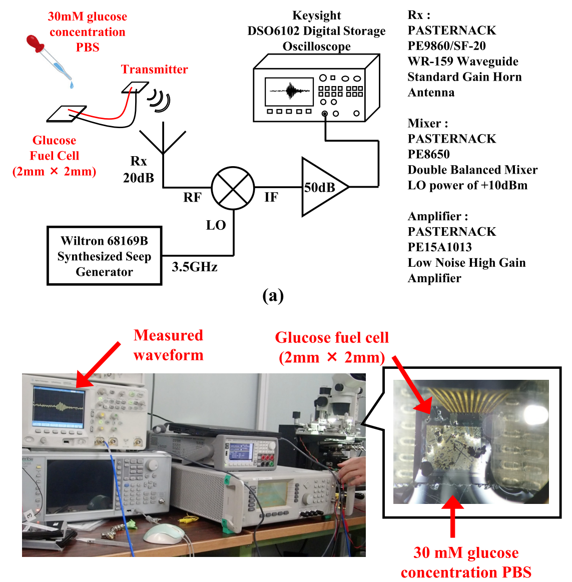
Table 1 Performance comparison among small form factor CMOS transmitters

	JSSC 2012 [4]	JSSC 2014 [12]	TCAS-I 2015 [10]	TCAS-II 2018 [7]	This Work
Process	130 nm	180 nm	32 nm SOI	55 nm DDC	65nm
Minimum power	3 μW	1.1 nW	3 nW	1.9 nW	0.27 nW
Operating voltage range	1.2 V	0.03 – 1.1 V	0.1 - 0.19 V	0.32 - 0.4 V	0.165 – 0.39 V
Off chip component	Off-chip antenna, electrode, sensor	Off-chip inductor, capacitor, antenna	Fully on-chip	Fully on-chip	Fully on-chip
Process characteristic	-	-	Deep-trench capacitors (250 fF/μm²)	Low leakage	-
Kick start	Needed	Needed	No needed	No needed	No needed
Wireless	2.4 GHz	-	33 GHz	4.87 GHz	4.1 GHz
Size	0.6 mm × 0.6 mm	9 mm × 11 mm *	0.3 mm × 0.3 mm	0.6 mm × 0.6 mm	0.385 mm × 0.385 mm

* Implantable sensor board size which designed to fit into human mastoid cavity

5. Demonstration of Self-Powered Operation with Glucose Fuel Cell

Figure 9 shows the measurement setup and transmission waveform of self-powered operation obtained with a solid-state glucose fuel cell whose size is 2 mm × 2 mm. The solid-state glucose fuel cell was fabricated using a CMOS-



(b)

Fig. 9 Measurement by connecting to 2 mm × 2 mm glucose fuel cell with 30 mM glucose concentration phosphate buffered saline (PBS): (a) measurement setup (b) obtained waveform.

compatible process [6], [13]. For use as both a power source and as a sensing transducer, the fuel cell was designed as an anode-limited fuel cell, whose output depends only on glucose concentration.

Self-powered operation of wireless transmission with 30 mM glucose concentration in phosphate buffered saline (PBS) was successfully verified. PBS was used as the base solution to simulate body fluid. Owing to the limited number of the fabricated glucose fuel cells, operation with smaller sizes and lower glucose concentrations could not be tested. Since normal tear glucose concentration is lower than 1 mM, further testing is needed for practical application. The increase in the number of samples improves the possibility of obtaining a fuel cell that operates at lower glucose concentrations. Results from a previous study on fuel cells show the possibility of a 0.6 mm × 0.6 mm fuel cell operating at 10 mM concentration [5], [6], [13].

6. Conclusion

In this work, we demonstrate a compact, low-voltage, and low-power fully-integrated CMOS OOK transmitter. The prototype chip fabricated using a standard 65 nm CMOS process demonstrates 0.27 nW power consumption with a supply voltage of 0.165 V. Self-powered wireless OOK transmission with a 2 × 2 mm^2 glucose fuel cell was also demonstrated. Our results show the potential realization of a glasses-free self-powered continuous glucose monitoring contact lens.

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