BRIEF PAPER *Special Section on Analog Circuits and Their Application Technologies*

An FSK Inductive-Coupling Transceiver Using 60 mV 0.64 fJ/bit 0.0016 mm^2 Load-Modulated Transmitter and LC-Oscillator-Based Receiver in 65 nm CMOS for Energy-Budget-Unbalanced Application

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SUMMARY This work presents an FSK inductive-coupling transceiver using a load-modulated transmitter and LC-oscillator-based receiver for energy-budget-unbalanced applications. By introducing the time-domain load modulated transmitter for FSK instead of the conventional current-driven scheme, energy reduction of the transmitter side is possible. For verifying the proposed scheme, a test chip was fabricated in 65 nm CMOS, and two chips were stacked for verifying the inter-chip communication. The measurement results show 0.64 fJ/bit transmitter power consumption while its input voltage is 60 mV, and the communication distance is 150 μm. The footprint of the transmitter is 0.0016 mm^2.

key words: *FSK, IoT, inductive-coupling, load modulation, low power*

1. Introduction

Today's IoT performance is limited mainly due to the energy-budget, implementation cost, and wireless connectivity. In edge-oriented application, energy-limited IoT edges must contain energy-efficient transmission capability. To address this issue, many attempts have been made, including near-field current-driven inductive-coupling transceivers [1] for energy-efficient proximity communication. The conventional inductive-coupling transceiver focused on the total energy efficiency, including both transmitter and receiver energy consumption, which resulted in 10 fJ/bit energy efficiency [2].

However, in IoT applications, the energy-budget-unbalanced application appears. For instance, in implantable electronics, the implanted tag has severe energy limitations, whereas the energy limitation is relatively relaxed in the reader. Thus, an energy-efficient transmitter is required. However, there is no report on development efforts focusing on transmitter energy minimization while sacrificing receiver energy efficiency, to the best of our knowledge.

This work presents the world's first inductive-coupling FSK transceiver using a load-modulated transmitter and LC-oscillator-based FSK receiver for energy-unbalanced applications, which enables energy-efficient and small-form factor transmission capability, to the best of our knowledge. The measurement results using the prototype test chip showed 0.64-fJ/bit transmitter energy consumption under a 60-mV input voltage. The receiver consumes 1 mW under a 380-mV input voltage.

The remainder of this paper is organized as follows. Section 2 introduces the proposed inductive-coupling FSK communication. Section 3 describes the circuit implementation and measurement setup. Section 4 shows its measured results. Section 5 concludes this study.

2. Inductive-Coupling FSK Communication

2.1 Motivation and Basic Structure

Figure 1 shows the performance benchmark of this work. This work has achieved the lowest transmitter energy, while achieving the lowest input voltage. Development of conventional inductive-coupling links focused on the minimization of total energy, including the transmitter and receiver energy. In this work, we have focused on minimization of transmitter energy while sacrificing receiver energy efficiency. There are many applications for energy-imbalanced conditions in this IoT era. Thus, this work will contribute to the advancement of these types of applications.

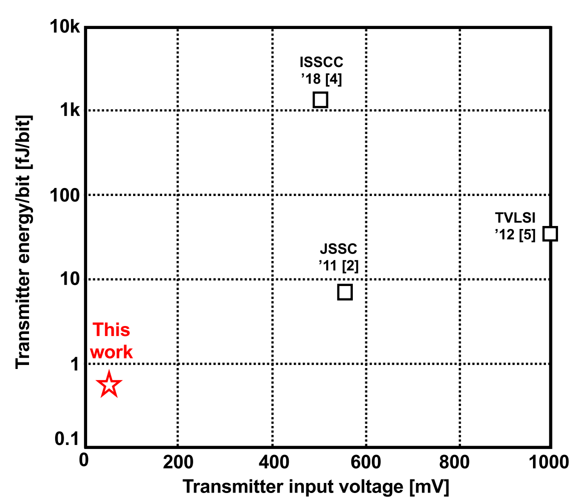

Fig. 1 Performance benchmark of this work.

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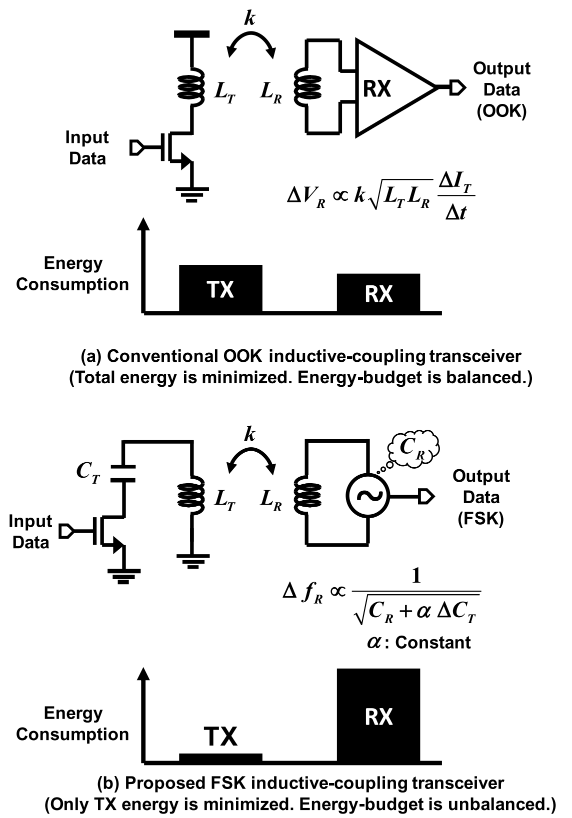

Fig. 2 Conventional and Proposed inductive-coupling transceiver: (a) conventional and (b) proposed transceiver.

In the conventional FSK communication method shown in Fig. 2 (a), the power oscillator is operated on the transmitter, and data is sent to the receiver by changing the oscillation frequency according to the information data bit. Data communication of this FSK system has a property that it is resistant to noise. The frequency does not affect it, as the amplitude noise primarily acts additively on the signal. However, on the transmitter, it is necessary to operate the power oscillator at all times, which requires a large amount of electric power, so it cannot be used in cases where electric power is limited.

Figure 2 (a) shows the current-driven inductive-coupling communication method [3]. As it can operate at a low voltage, it can be used even in a situation where only a low voltage can be obtained. However, it has the disadvantage that it is vulnerable to environmental noise. If noise is superimposed on the modulated wave, it will be mistakenly demodulated on the receiver.

In addition, when it is mounted on a sensor, or a similar device which operates with low power consumption, it consumes the majority of the total power consumption of the circuit architecture, so it becomes a big problem in cases where energy is limited, such as in an energy harvester.

In this paper, we propose an inductive-coupling FSK communication method that is resistant to noise and has a low voltage and low power consumption on the transmitter. Thus, even when only low power can be obtained, such as when using a biofuel cell, it can operate as a sensor and send information to the receiver.

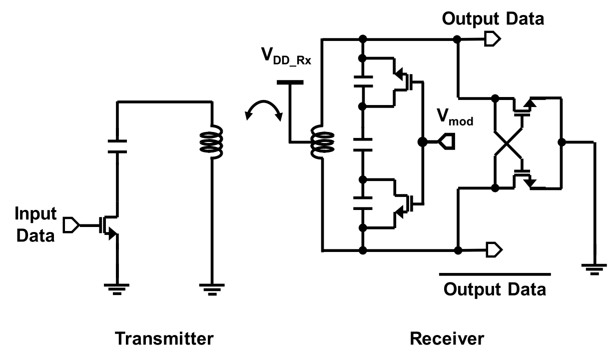

Fig. 3 Circuit diagram of the proposed inductive-coupling FSK communication.

A conceptual diagram of the proposed inductive-coupling FSK communication method is shown in Fig. 2 (b). In the figure, L_T, L_R, C_T, C_R, k, and α denote the transmitter inductance, receiver inductance, transmitter capacitance, receiver parasitic capacitance, coupling coefficient, and modulation constant, respectively. It consists of a transmitter with a load modulation circuit and a receiver with an LC oscillator, which consumes more power. This oscillator is an LC power oscillator whose oscillation frequency varies depending on the inductance and the capacitance. When inductively coupled with the transmitter, the oscillation frequency is determined by not only the capacitance and inductance of the transmitter, but also the capacitance and inductance of the receiver. The load modulation circuit on the transmitter is operated to change the value of the LC oscillator capacitance. This makes the oscillation frequency of the LC oscillator change, so it can send a data bit stream. As only the load modulation circuit is operated on the transmitter, it has a considerably lower power consumption than the conventional communication method.

2.2 Load Modulated Transmitter and LC Cross-Coupled Oscillator Based FSK Receiver

Figure 3 shows the detailed circuit diagram of the proposed inductive-coupling FSK communication system. The inductor, capacitor, and NMOS are connected in series on the transmitter side. Since there is no DC path from transmitter input voltage to ground, extremely low energy can be achieved. Only gate leakage power from the NMOS is consumed.

The NMOS transistors and capacitors are connected in parallel on the LC oscillator on the receiver side so that the parallel capacitance can be adjusted. As a result, when the resonance frequency fluctuates owing to variations in parasitic components and processes, the capacitance can be adjusted by changing the gate voltage of the transistor (Vmod) to adjust the resonance frequencies of the transmitter and receiver. This makes large frequency modulation.

Figure 4 shows the timing chart of the proposed

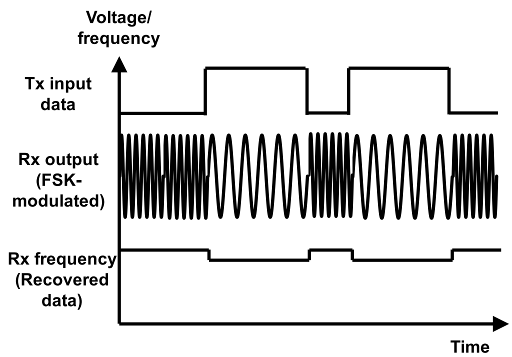

Fig. 4 Timing chart of the proposed inductive-coupling FSK communication.

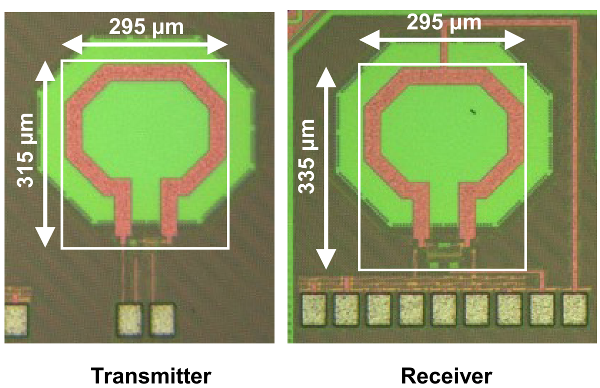

Fig. 5 Chip microphotograph for inter-chip communication.

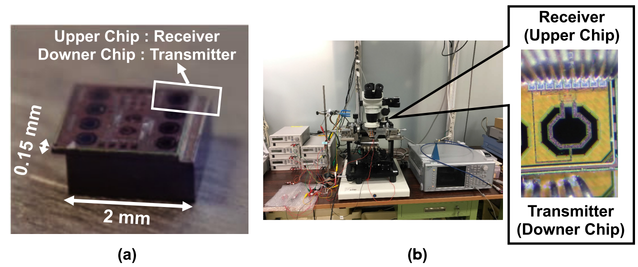

Fig. 6 Bird's eye microphotograph of the stacked chips (a) and its measurement setup (b).

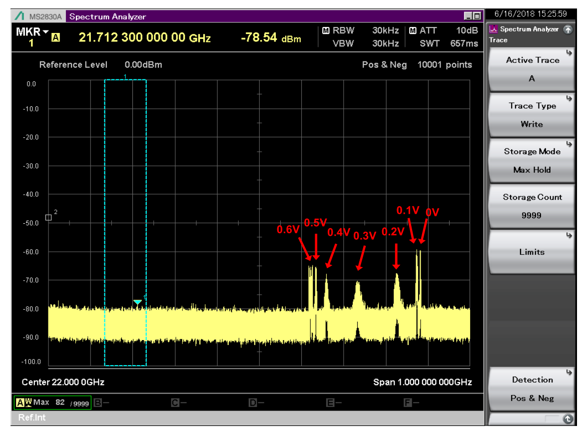

Fig. 7 Measured spectrum obtained from the chip where the transmitter input voltage changes from 0.1 V to 0.6 V.

inductive-coupling FSK communication system. The transmitter data are fed into the gate of NMOS transistor connected in series to the load capacitor. By switching the NMOS, the capacitance of the transmitter can be changed. Through inducitve-coupling, the output frequency of LC-oscillator-based receiver can be modulated.

By using a high-frequency LC oscillator on the receiver side, FSK modulation with low energy can be obtained. Energy efficiency can be optimized by optimizing the channel characteristics.

3. Test-Chip Design and Measurement Setup

A prototype test chip was fabricated in 65 nm CMOS technology. Figure 5 shows the micrograph of the test chip. The area including the on-chip antenna of the transmitter is $315\,\mu$m $\times$ $295\,\mu$m and that of the receiver is $335\,\mu$m $\times$ $295\,\mu$m. The area of the core circuit excluding the antenna of the transmitter is $80\,\mu$m $\times$ $20\,\mu$m and that of the receiver is $40\,\mu$m $\times$ $10\,\mu$m.

In order to investigate the performance in an actual scenario, we stacked the fabricated test chips. To adjust the communication distance to $150\,\mu$m, the thickness of the upper chip was reduced to $150\,\mu$m by employing the back grinding technique. Figure 6 (a) shows a bird's eye view of the stacked chips.

Figure 6 (b) shows the measurement setup. We utilized a manual probing technique with a probe station (alpha 150, Apollowave Corp.). A spectrum analyzer (Anritsu MS 2380A, ~43 GHz) was utilized for detecting output frequency.

4. Measurement Results

4.1 Results of Inter-Chip Communication

Figure 7 shows the spectrum obtained from the LC oscillator on the receiver side by using the gain horn antenna (PASTERNACK, PE9852/2F-20), while the input voltage to the load modulation circuit of the transmitter is changed. The oscillation frequency of the receiver is approximately 22.4 GHz.

The frequency is determined to be as high as possible in our measurement setup. By changing the transmitter load, it can be confirmed that the transmission frequency on the receiver side is changing through inductive coupling.

Figure 8 shows the spectrum when the transmitter input voltage is 60 mV. A frequency shift was successfully confirmed at an input voltage of 60 mV, which is much greater than the typical jitter value. Because the transistor gate capacitance of the load modulation circuit is designed to be 64 fF, the power consumption of the transmitter is presumed to be 0.64 fJ/bit. This is the transmitter with the lowest power consumption in the world. As the input voltage increases, the amount of frequency shift also increases and

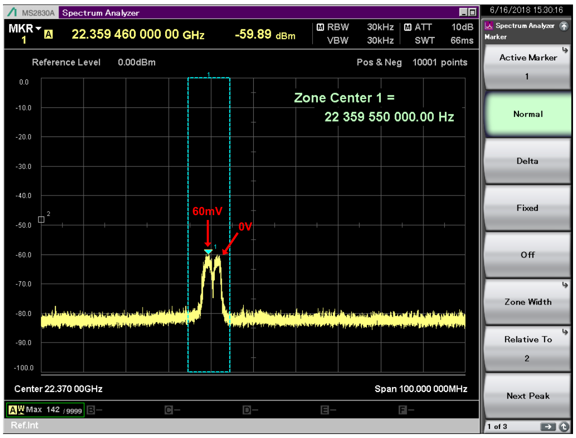

Fig. 8 Measured spectrum obtained from the chip where the transmitter input voltage is 60 mV.

Table 1 Comparison table.

	JSSC 2011 [2]	ISSCC 2018 [4]	This Work
Process	65 nm	65 nm	65 nm
Coupling	Inductive	Inductive	Inductive
Transmitter input voltage	0.55 V	0.5 V	60 mV
Transmitter energy	5.3 fJ / bit	1.5 pJ / bit	0.64 fJ / bit
Distance	22 μm	11 mm	150 μm
Transmitter coil diameter	110 μm	10 mm	220 μm
Receiver coil diameter	110 μm	10 mm	220 μm
Coupling coefficient	0.68 *	0.06 *	0.195 *

* Estimated value by layout image of the inductors.

saturates at 0.7 V.

4.2 Performance Evaluation

Table 1 shows the performance comparison among the energy-efficient inductive-coupling communication methods [2], [4]. The proposed inductive-coupling FSK communication method outperforms the other method in terms of transmitter power consumption and input voltage. The proposed technique also outperforms the previous reports [1], [3], [5]–[7].

The objective of this study is to reduce consumption on the transmitter side for energy-budget-unbalanced applications. Thus, the energy on the receiver side was increased considerably. The proposed LC-oscillator-based FSK receiver consumes 1.2 mW power, which corresponds to 12 pJ/bit when the data rate is 100 Mbps, which is the measured maximum data rate. Thus, from the viewpoint of the total energy reduction, the proposed approach is not desirable. However, in energy-budget-unbalanced applications, the proposed approach is the most effective.

Because of the limited bandwidth of I/O circuits for TX input data, the measured maximum data rate was limited to 100 Mbps. The SPICE simulation shows the data rate can be increased up to 3 Gbps.

From the viewpoint of total power reduction, the proposed approach is not the best because the receiver power becomes higher. However, in IoT-era, energy-budget-unbalanced application such as the bio-fuel-cell-operated transmitter [8]–[10] appeared. Thus, the proposed approach will be beneficial for practical application.

5. Conclusion

In this paper, we proposed an inductive-coupling FSK transceiver using load-modulated transmitter and LC-oscillator-based receiver for energy-budget-unbalanced applications. The measurement of the stacked test chips using 65 nm CMOS technology demonstrated 60 mV and 0.64 fJ/bit TX operation. This approach was found to be effective in energy-budget-unbalanced applications.

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