An Energy-Harvesting Wireless-Interface SoC for Short-Range Data Communication

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Keywords: RF, Energy harvesting, SoC, Low power, Wireless, Battery-less operation

Conventional wireless short-range data-communication devices usually require a battery for power supply, which is disadvantageous from viewpoints of weight, cost, and adverse environmental effects. For that purpose, an ultra low-power SoC (system-on-a-chip) with a wireless interface is required and energy-harvesting capability have to be realized. In this study, we demonstrate both ultra low-power design and parts-number minimization by applying SoC implementation. The target is set to a wireless battery-less mouse. The wireless battery-less mouse is environmental-friendly since it does not have a battery.

The SoC consists of an RF transmitter and microcontroller as illustrated in Fig. 1. The direct modulation scheme is adopted in the RF transmitter for low-power consumption since it has simple structure. Consequently, transistor counts are reduced and passive elements are minimized. The microcontroller contains a 16-bit CPU, 1-kB RAM and peripherals. The design dedicated for mouse operation reduces the gate count and clock frequency to 1 MHz, in turn achieves low-power operation.

The test chip including the RF transmitter and microcontroller was fabricated by a TSMC 0.18-μm CMOS mixed-signal-technology with one poly and six metal layers. Figure 2 shows a photograph of the SoC.

The experimental results show that the microcontroller can operate at a supply voltage of 1 V and an operation frequency of 25 MHz. However, we operate the SoC at 1 V and 1 MHz to achieves low-power operation. And the RF transmitter performs a stable FSK modulation, which is successfully synchronized with transmission data. The induced voltage at a loop antenna on a receiver side sustains 680 μV still in the 1-m range. Since 100 μV is supposed to be sufficient for a receiver, the RF transmitter demonstrates communication in a 1-m range. At the supply voltage of 1 V, the RF transmitter consumes 2.17 mW. The microcontroller consumes 33.35 μW, which is negligible compared to that of the RF transmitter. The total power consumption is 2.2 mW, which is sufficient for electric generator to make 1-m range communication. This demonstrates that the SoC can operate using the harvested electric power.

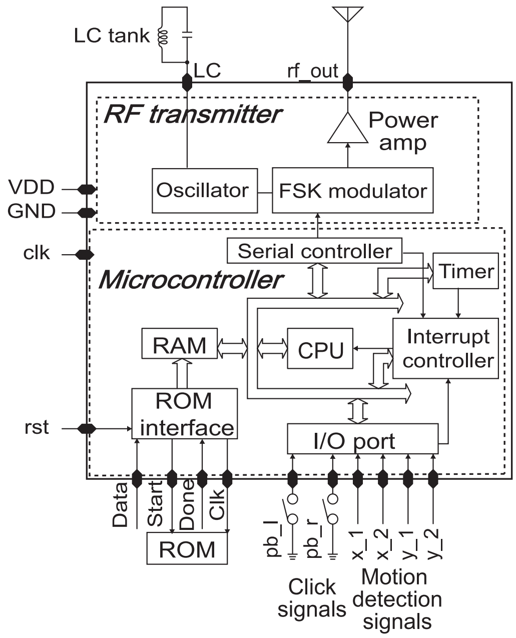

Fig. 1.　Block diagram of SoC

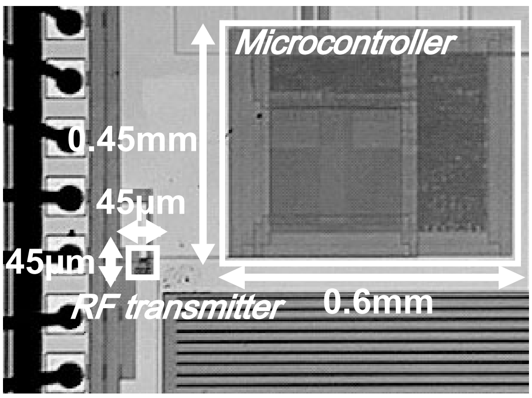

Fig. 2.　Chip photograph

Paper

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This paper describes design and verification of a wireless-interface SoC (system-on-a-chip) for a wireless battery-less mouse with short-range data-communication capability. The SoC comprises an RF transmitter and microcontroller. The SoC, which is powered by an electric generator that exploits gyration energy by dragging the mouse, was fabricated using a TSMC 0.18-um CMOS process. The features of the SoC are the adoption of a simple FSK modulation scheme, single-end configuration on the RF transmitter, and specific microcontroller design for mouse operation. We verified that the RF transmitter can make data communication within a 1-m range at 2.17 mW, and the microcontroller consumes 0.03 mW at 1 MHz, which exhibits that the total power consumption is 2.2 mW. This is sufficiently low for the SoC to operate with energy harvesting.

Keywords: RF, Energy harvesting, SoC, Low power, Wireless, Battery-less operation

1. Introduction

Conventional wireless short-range data-communication devices usually require a battery for power supply, which is disadvantageous from viewpoints of weight, cost, and adverse environmental effects. However, in order to achieve a ubiquitous network, it is preferable to have wireless interfaces and operate in battery-less environment, for which purpose an ultra low-power SoC (system-on-a-chip) with a wireless interface is required and energy-harvesting capability have to be realized. Thus, it is better that there is an electric generator inside the device, but electric generator offers only a small electric generation capacity. Furthermore, the electric power generator should be implemented in a limited space.

In this study, we demonstrate both ultra low-power design and parts-number minimization by applying SoC implementation. The target is set to a wireless battery-less mouse. As we know, wireless mice are convenient; they have penetrated the market rapidly. The wireless battery-less mouse is environmental-friendly since it does not have a battery.

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2. Electric Generator

2.1 Mechanism Figure 1 shows the mechanism of the electric generator in the wireless battery-less mouse. Crankshafts are placed in both X and Y directions. When the mouse is dragged, a mouseball spins, and then the crankshaft is rotated by gears. Two magnets are connected to the crankshaft, and put in and out of coils in dynamos. Thereby, electromotive force is indecued, which is used as electric power for the SoC.

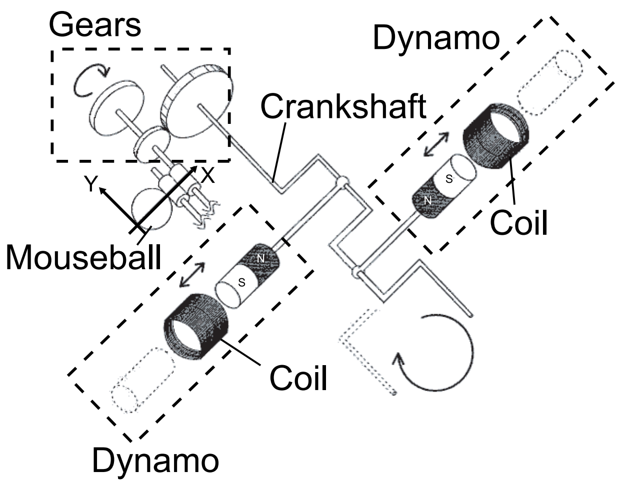

Fig. 1. Mechanism of electric generator in X direction

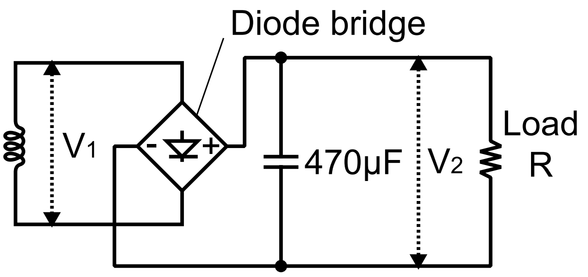

Fig. 2. Measurement setup for generated power

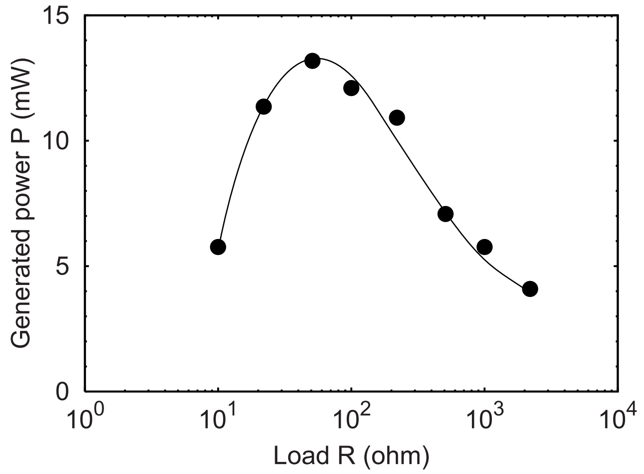

Fig. 3. Measurement result of generated power

2.2 Measurement of Generated Electric Power Generated electric power was measured in the circuit shown in Fig. 2. The generated voltage, V_1, is rectified with a diode bridge. The output voltage, V_2, are to be measured, and the generated electric power, P, is calculated as follows;

$$P = \frac{V_2^2}{R}.$$

The moving frequency of the magnet is about 40–50 Hz (shuttling 20–25 times per second). Figure 3 shows the measurement result of the generated power, which shows that the electric generator can generate 4–13 mW depending on the load. However, in consideration of a safety margin and efficiency in the rectifier and a DC-DC converter for the SoC, the power consumption of the SoC must be suppressed to less than 3 mW.

3. SoC Implementation

3.1 Requirement Specification In order to store electric generators and other electronics inside the mouse, it is necessary to minimize the number of parts used in a mouse. In this study, we achieve low-power characteristics and minimization of the number of parts, not only through low-power design of an RF circuit, but also through SoC (System-on-a-Chip) implementation. Therefore, the RF circuit and another digital parts are on the same SoC. The required specifications of SoC are summarized as follows;

- Power consumption: less than 3 mW
- Modulation method: FSK (frequency shift keying)

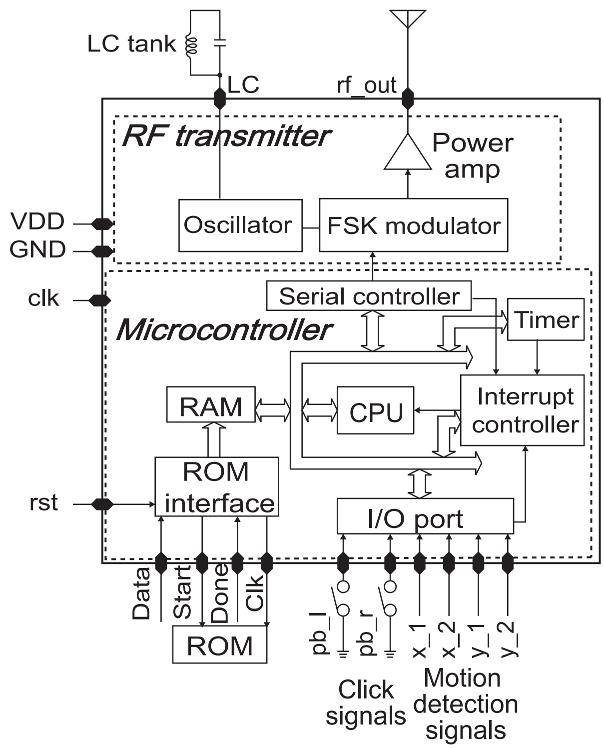

Fig. 4. Block diagram of SoC

- Carrier frequency: 27.8 MHz (same as commercially available mice)
- Communication distance: 0.2–1 m
- Data rate: 10 kbps

3.2 Block Diagram The SoC consists of an RF transmitter and microcontroller as illustrated in Fig. 4. The direct modulation scheme described later is adopted in the RF transmitter for low-power consumption since it has simple structure (2). Consequently, transistor counts are reduced and passive elements are minimized. The microcontroller contains a 16-bit CPU, 1-kB RAM and peripherals. The design dedicated for mouse operation reduces the gate count and clock frequency to 1 MHz, in turn achieves low-power operation. The ROM is for code memory. The click signals and motion detection signals in the X and Y directions are processed with the microcontroller.

3.3 Motion Detection Signals The microcontroller has to detect the motion of the mouse which is transformed to specified signals by optical sensors apart from the SoC.

Figure 5 shows the motion detector in the X direction. The wheel with slits rotates synchronizing with the X-axis movement. The white box in the figure is a light source and projects light through the slits to the two optical sensors. The optical sensors can detect the light and discriminate either dark or bright. The light source and optical sensors are separated about 1 mm.

Figure 6 shows the motion detection signals of the X directions. The motion detection signals are composed of two signals that indicate a rotation direction and speed. The rotation direction is detected by the relationship between two rising edges. The rotation speed

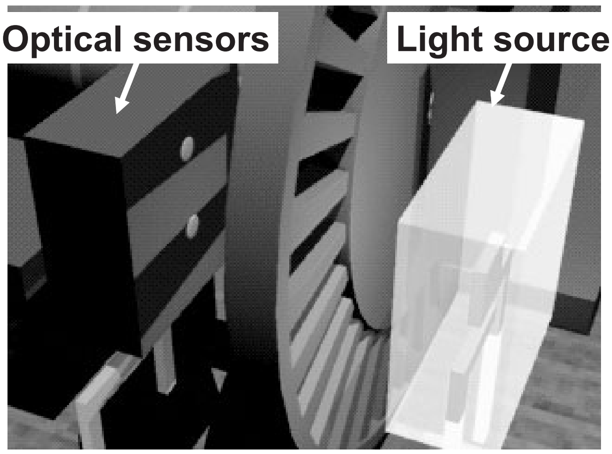

Fig. 5. Motion detector (4)

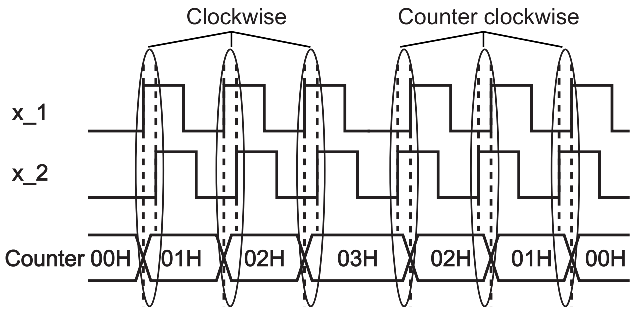

Fig. 6. Motion detection signals

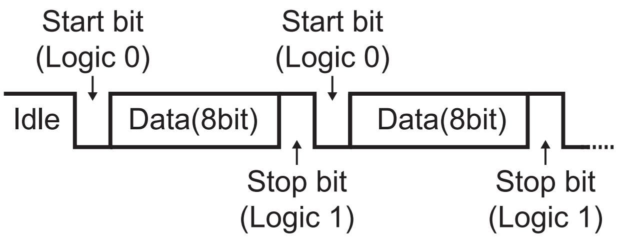

Fig. 7. Serial data format for information of mouse motion

is detected with a hardware counter counting the number of pulses.

3.4 Operations of SoC The operations of the SoC are summarized as follow;

(1) The motion detection signals and click signals are input through I/O ports and fed forward to a interrupt controller.

(2) The interrupt controller interrupts a 16-bit CPU at a fixed interval using a timer, and then the CPU reads the hardware counter. The CPU transforms the direction and speed of the mouse into a specific data format (see Fig. 7).

(3) Data are serialized using a serial controller and forwarded to the RF transmitter block.

(4) The RF transmitter block modulates them to FSK, and transmits the serialized data through the rf_out terminal.

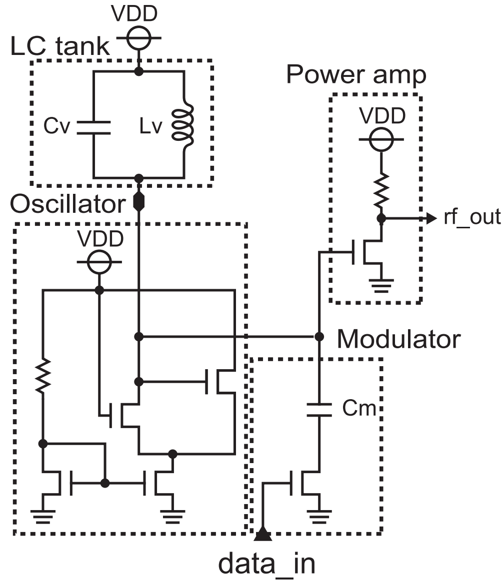

Fig. 8. Circuit diagram of RF transmitter

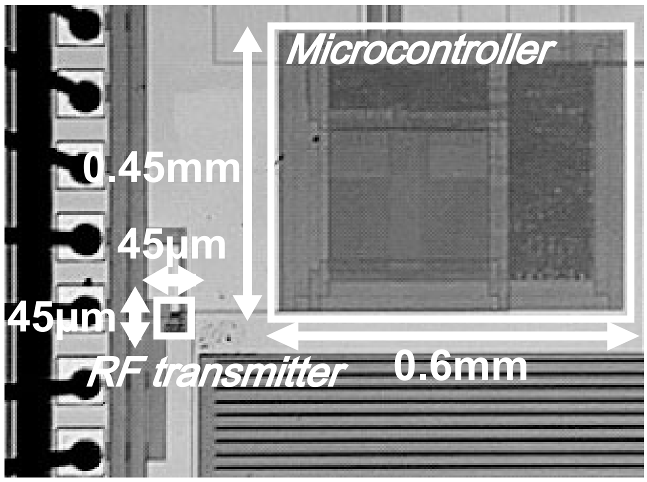

Fig. 9. Chip photograph

4. RF Transmitter

Figure 8 shows a circuit diagram of the RF transmitter. A negative-impedance-type circuit is adopted for an oscillator which is simple and has low-power characteristics. Moreover, the single-end scheme is applied to reduce the number of transistors. The modulation is performed by changing resonance frequency of a LC tank with Cm. The resonance frequency is adjusted to 27.8 MHz in advance.

The wavelength of the carrier is the same as that of off-the-shelf wireless mice and is about 11 m. Because the communication distance is sufficiently shorter than the wavelength, magnetic coupling is used for the communication.

5. Test Chip Micrograph

The test chip including the RF transmitter and microcontroller was fabricated by a TSMC 0.18-μm CMOS mixed-signal-technology with one poly and six metal layers. Figure 9 shows a photograph of the

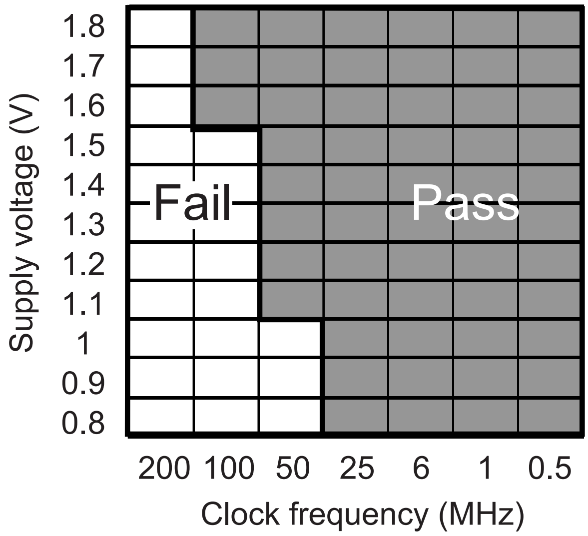

Fig. 10. Shmoo plot of microcontroller

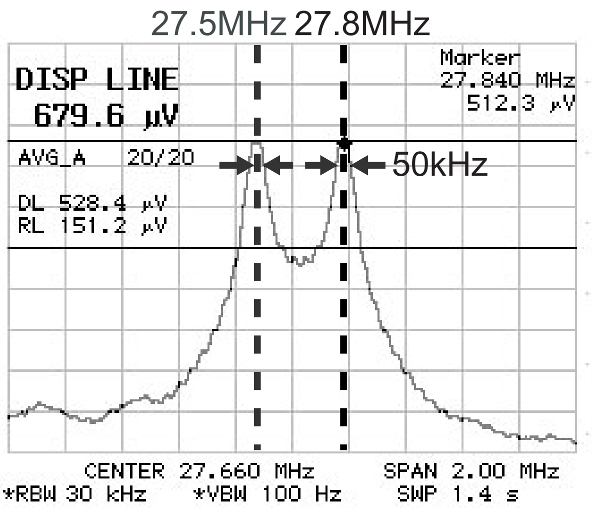

Fig. 11. Spectrum diagram from RF transmitter

SoC. The size of the microcontroller that has 6,000 gates is 0.45×0.6 mm^2. The RF transmitter size is 45×45 μm^2.

6. Experimental Results

6.1 Microcontroller Figure 10 shows a shmoo plot of the microcontroller. The microcontroller can operate at a supply voltage of 1 V and an operation frequency of 25 MHz. However, we operate the SoC at 1 V and 1 MHz to achieves low-power operation. The microcontroller potentially works at 100 MHz at a supply voltage of 1.5 V.

6.2 RF Transmitter Figure 11 shows a spectrum diagram observed at a distance of 1 m. The figure indicates two peaks at frequencies of 27.5 MHz and 27.8 MHz, which exhibits the proper operation. The bandwidths are 50 kHz.

Figure 12 shows transient characteristics of the output frequency at an input-data frequency of 100 kHz, obtained using a jitter analysis function of an oscilloscope. The figure indicates that the RF transmitter performs

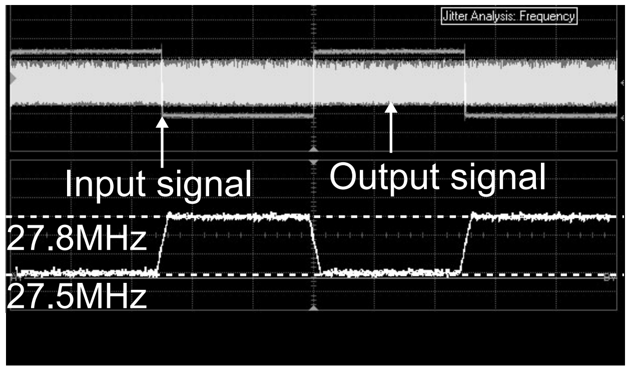

Fig. 12. Transient characteristics of output frequency

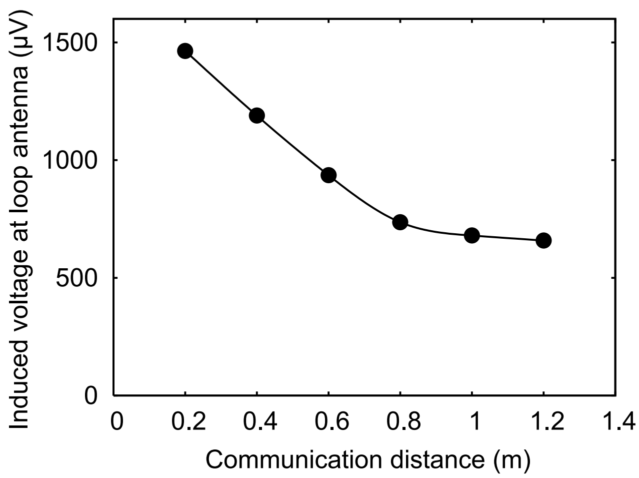

Fig. 13. Characteristics of induced voltage versus communication distance

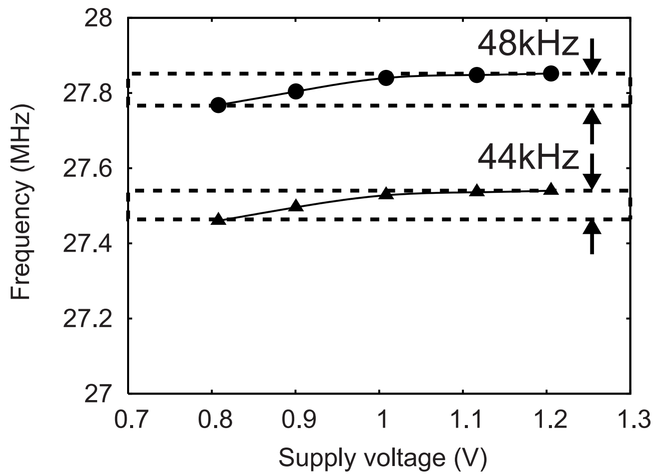

Fig. 14. Frequency variation when supply voltage changes

a stable FSK modulation, which is successfully synchronized with transmission data.

Figure 13 shows induced-voltage characteristics at a loop antenna on a receiver side for different communication distances. The induced voltage sustains 680 μV still in the 1-m range. Since 100 μV is supposed to be sufficient for a receiver, the RF transmitter demonstrates communication in a 1-m range.

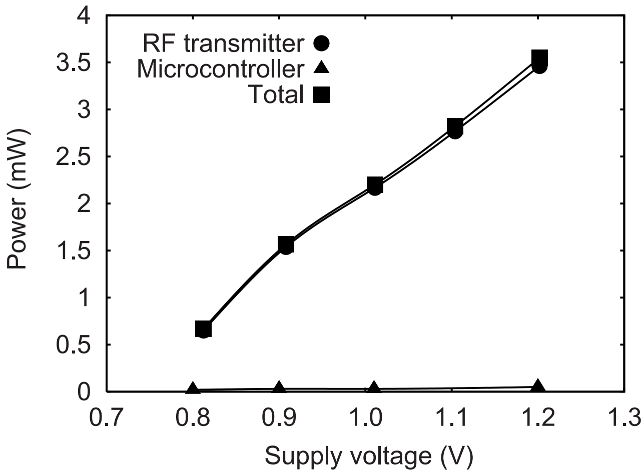

Fig. 15. Power characteristics

Figure 14 indicates frequency variation when a supply voltage changes. In energy harvesting, the supply voltage is supposed to be varied in a wide range. Thus, the resonance frequency is trimmed with the external capacitance of the LC tank at a nominal voltage of 1V. As shown in fig. 14, the frequency variation is smaller than the bandwidth of 50 kHz, which means the SoC is tolerant of the supply voltage variation, and possible to correctly detect symbols on a receiver side.

Figure 15 shows power dependence on a supply voltage. The clock frequency of the microcontroller is 1 MHz that is sufficient to properly count the number of pulses in mouse operation. At the supply voltage of 1 V, the RF transmitter consumes 2.17 mW. The microcontroller consumes 33.35 μW, which is negligible compared to that of the RF transmitter. In total, the power is 2.2 mW.

7. Conclusions

An ultra-low-power wireless-interface SoC for short-range data-communication that realizes a wireless battery-less mouse was designed and verified. The mouse uses rotational movement to generate electric power, and operates using the electric power. The SoC consists of an RF transmitter and microcontroller. The experimental results show that the RF transmitter consumes 2.17 mW and thus dominates the power, while the microcontroller consumes 0.03 mW. The total power consumption is 2.2 mW, which is sufficient for electric generator to make 1-m range communication. This demonstrates that the SoC can operate using the harvested electric power.

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