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A Wireless-Interface SoC Powered by Energy Harvesting for Short-range Data Communication

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

I. Introduction

Conventional wireless short-range data communication devices require a battery for a power supply, which is disadvantageous from the viewpoints of weight, cost, and adverse environmental effects. In addition, for realization of a ubiquitous network, it is desirable for those devices to have wireless interfaces and operate in a battery-less environment. For that purpose, an ultra low-power system LSI with a wireless interface is required. It must operate using electric power harvested from the environment. However, energy harvesting offers only a small electric generation capacity. Furthermore an electric power generator should be implemented in a limited space. In this study, we tried to achieve both ultra low power and parts number minimization by applying a low power design of RF circuit and System-on-Chip implementation.

The target was set to a wireless battery-less mouse. Wireless mice are convenient; they have penetrated the market rapidly. Computer mouse utility has been improved further and prevention of environmental pollution by careless abandonment of batteries can be realized by use of a wireless battery-less mouse that incorporates an electric generator.

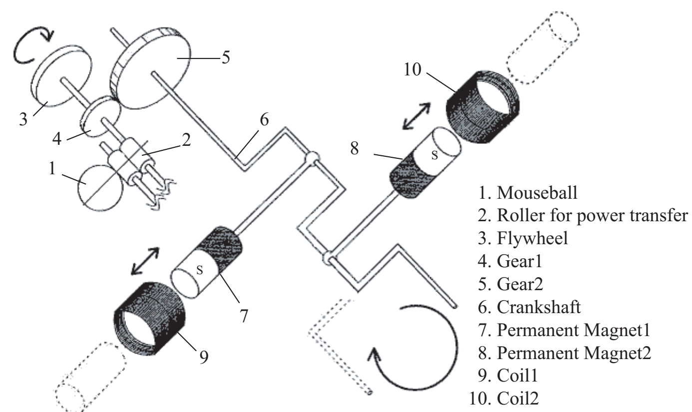

Fig. 1. Mechanism of electric generator

II. Electric Generator

A. Mechanism

Figure 1 shows the mechanism of an electric generator of the wireless battery-less mouse. A crankshaft is placed in both the X and Y directions into the mouse. The gyration energy of the shaft is increased with the gear. A magnet is passed into and out of a coil by the energy; thereby, induced electromotive force is generated. This is used as electric power for LSI to operate.

B. Measurement of Generated Electric Power

Generated electric power is measured using a circuit diagram shown in Fig. 2. Voltage V1 and V2 are measured and the generated electric power P is calculated as

$$P = \frac{V2^2}{R}.$$

The moving frequency of the magnet is about 40–50 Hz (shuttling 20–25 times per second). Table I shows the measurement result. This result shows that the electric generator

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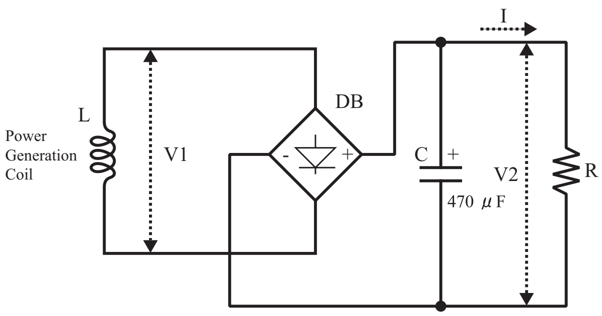

Fig. 2. Circuit diagram of induced voltage measurement

TABLE I
MEASUREMENT RESULT

R (ohm)	V1 (V)	V2 (V)	P (mW)
10	2.90	0.24	5.76
22	3.00	0.50	11.36
51	3.80	0.82	13.18
100	4.40	1.10	12.10
220	5.30	1.55	10.92
510	6.40	1.90	7.08
1000	6.40	2.40	5.76
2200	6.60	3.00	4.09

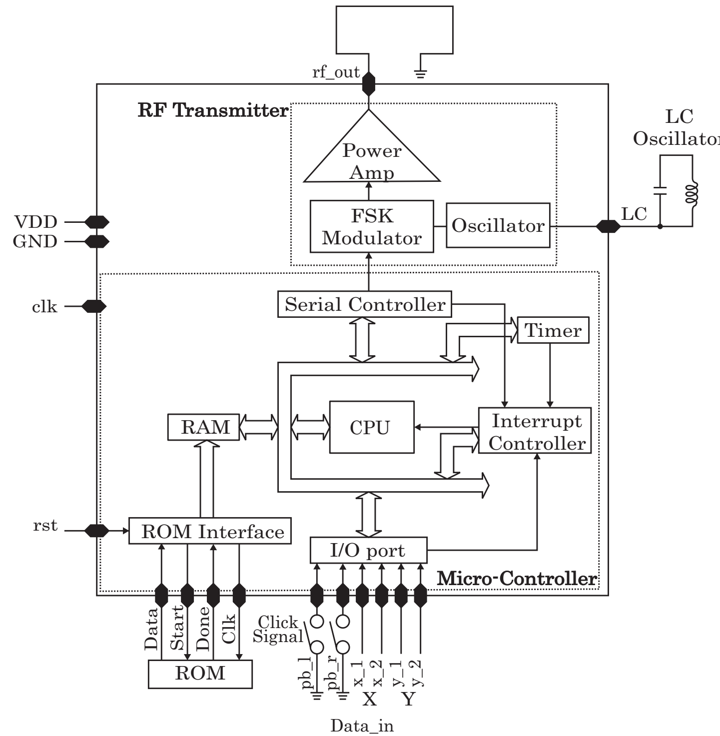

Fig. 3. Block diagram of SoC

can generate about 4–13 mW depending on a load resistance value. However, in consideration of efficiency in circuits such as those of a rectifier, a DC-DC converter and so on, power consumption of the LSI must be suppressed to less than 3 mW.

III. SoC Implementation

A. Requirement Specification

It is necessary to minimize the number of parts used in a mouse to store the electric generator and other electronics within the mouse. In this study, we achieved ultra low power and parts number minimization not only through the low power design of the RF circuit, but also through System-on-Chip implementation. The required specifications of SoC are summarized as follows.

- Power consumption: less than 3 mW
- Modulation method: FSK (Frequency Shift Keying)
- Carrier frequency: 28 MHz (same as the commercially available mouse)
- Communication distance: 0.2–1 m
- Data rate: 10 kbps

B. SoC Block Diagram

The SoC consists of an RF transmitter and microcontroller, as illustrated in Fig. 3. The direct modulation scheme has been adopted for the RF transmitter for simplification. Consequently, circuit counts were reduced and passive elements were quantitatively minimized. The microcontroller block contains a 16-bit CPU ,1 kB RAM and peripherals. A design specified for mouse operation reduces the gate count and reduces the clock frequency to 1 MHz.

C. Outline of Operation

The microcontroller in the SoC detects a click operation of a mouse and motion toward the X and Y directions. The outline of operations is summarized as follow;

1) The Motion Detection Signal that is generated by the motion of a mouseball and click signal is inputted into the I/O port.
2) The Motion Detection Signal is fed into the Interrupt Controller.
3) The Interrupt Controller is connected with a Timer. The Timer counts the number of pulses corresponding to a motion of the mouseball at a fixed interval.
4) The 16-bit CPU transforms the direction and distance of mouse operation into a specific data format (See Fig. 4).
5) Data are serialized using the Serial Controller and transferred to the RF Transmitter block.
6) The RF Transmitter block modulates and transmits the data.

IV. RF Transmitter Block

Figure 5 shows a circuit diagram of the RF transmitter. The RF transmitter block modulates transmitted data to the FSK

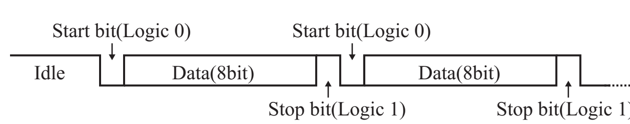

Fig. 4. Serial data format

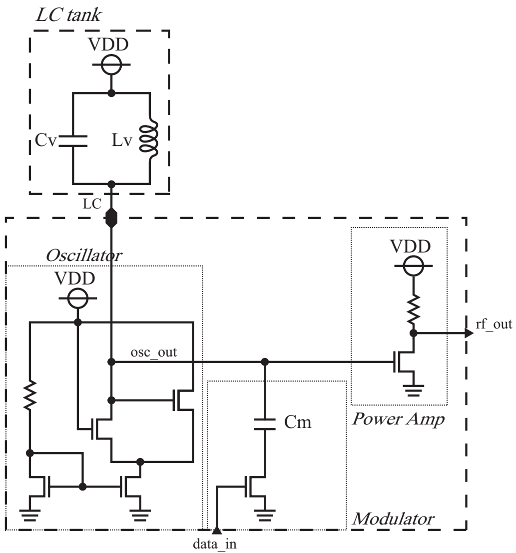

Fig. 5. Circuit diagram of the RF transmitter

signal of 28 MHz. A negative-impedance type circuit has been adopted for the oscillator block, which is very simple and has very low power characteristics. Moreover, single-end schemes have been adopted to reduce the number of required parts. Modulation is performed by changing the oscillation frequency according to transmitted data by whether a capacitor is inserted into the LC tank of an oscillator in series.

V. Estimation of the Distance that can be communicated

A. Estimation of Generated Magnetic Field Strength

The RF-transmitter carrier frequency is 28 MHz; its wavelength λ is about 10.71 m. The target communication distance of a wireless mouse is 1 m. Because the communication distance is shorter than the wavelength, the magnetic coupling is used for communication. The magnetic coupling is realized using a loop antenna for both the transmitter and receiver. The generated magnetic field was calculated theoretically considering the size of the antenna in the mouse. The Biot-Savart law is used for calculation and the magnetic field strength is estimated in distant positions by a(m) horizontally. The induced voltage at the standard loop antenna and the electric field strength are calculated using an antenna factor. The antenna factor value converts the induced voltage into the magnetic field strength and electric field strength. An active loop antenna (6502; EMCO) was used as a standard loop antenna. The formulas used to calculate the induced voltage and electric field strength using magnetic field strength are shown below.

$$Vant(dBV) = H(dBA/m) - AFH(dB) \quad (1)$$
$$= H(dBA/m) + 41.8 \quad (2)$$
$$(3)$$

where Vant (dBV) is the induced voltage, H (dBA/m) is the magnetic field strength, and AFH (dB) is the antenna factor for the magnetic field.

It is supposed that the size of the antenna incorporated into a mouse is 5 cm $\times$ 10 cm using copper wire with width of 1 mm. Table II shows estimation results. This table indicates that induced voltage is 124 μV at a 1-m range, consuming 2.5 mW in a RF transmitter circuit. Therefore, assuming more than 100 μV of induced voltage at the antenna on the receiver side, it is seen that the power consumption required to communicate in a 1-m range is almost 2.5 mW.

TABLE II
Estimation of Induced Voltage at the Standard Loop Antenna

Power consumption (mW)	range (m)	Magnetic field strength (A/m)	Induced volttage(V)
1.5	3	$22.7n$	2.8μ
	1	$557n$	69μ
	0.2	44.4μ	$5.5m$
2.5	3	$40.8n$	5.0μ
	1	1.0μ	124μ
	0.2	80.0μ	$9.83m$
3.5	3	$57.1n$	7.0μ
	1	1.4μ	173μ
	0.2	111.7μ	$13.7m$

VI. Experimental Results

The SoC was fabricated by the TSMC 0.18 um CMOS Mixed Signal 1P6M process and evaluated. Figure 6 shows a photograph of the SoC.

A. RF Transmitter

Figure 7 shows the spectrum observed at a 1-m range and Fig. 8 shows the transient characteristics of the output signal frequency at the input data frequency of 100 kHz. Transient characteristics were observed using the jitter analysis function of an oscilloscope. This figure suggests that the RF transmitter can perform a stable FSK modulation, which is synchronized with the transmit data. Figure 9 shows the induced voltage characteristics for a loop antenna for different

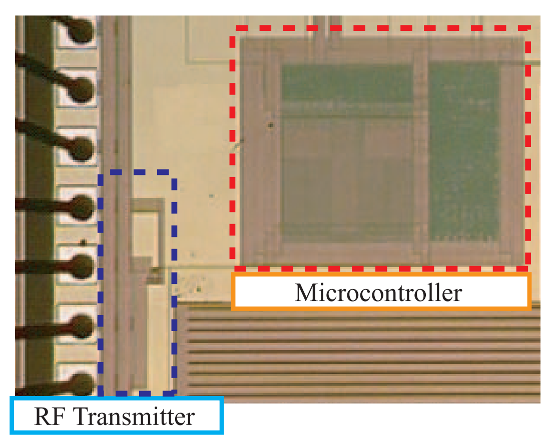

Fig. 6. Chip photograph

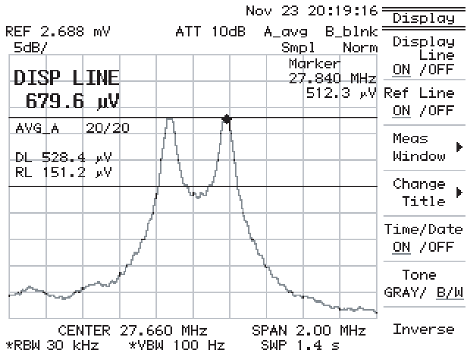

Fig. 7. Observed spectrum at a 1-m distant position

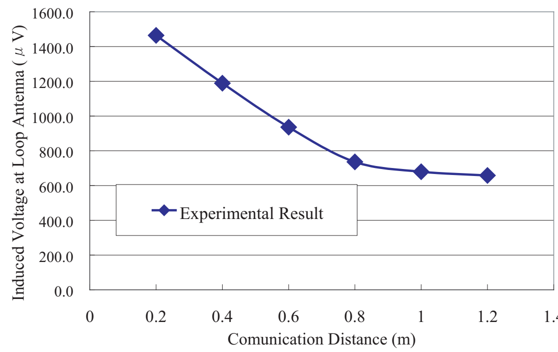

Fig. 9. Induced voltage characteristics versus communication distance

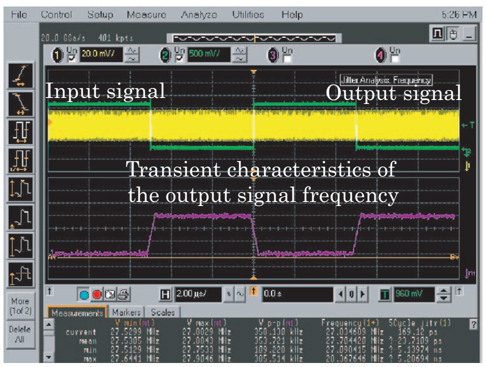

Fig. 8. Transient characteristics of the output signal Frequency

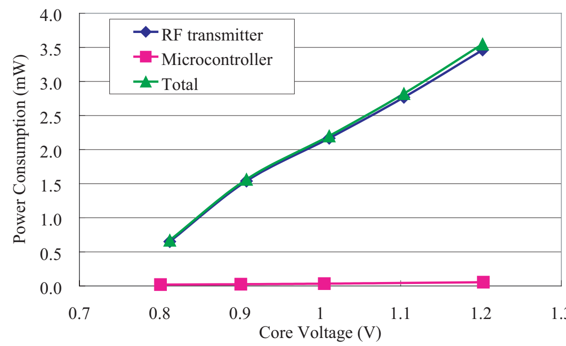

Fig. 10. Power consumption versus core voltage

communication distances. At a 1-m range, the induced voltage is 680 μV. Therefore, sufficient induced voltage was obtained to realize communication in a 1-m range. Figure 10 shows power consumption characteristics for various supply voltages. The RF transmitter consumed 2.17 mW at the supply voltage of 1 V. Therefore, our target power consumption for the RF transmitter (less than 2.5 mW) is also achieved.

B. Microcontroller

Figure 11 shows a shmoo plot for the microcontroller block. The microcontroller block can operate at a supply voltage of 0.8 V up to 25 MHz and achieve a maximum clock frequency of 100 MHz at a supply voltage of 1.8 V. The power consumption of a microcontroller block at the clock frequency of 1 MHz is plotted in Fig. 10. If it is a frequency of 1 MHz or less, it is sufficient for the count of the number of pulses in mouse operation. It consumed 33.35 μW at the supply voltage 1 V.

VII. Conclusion

An ultra low power wireless-interface SoC for short-range data communication was designed and evaluated to realize a wireless battery-less mouse. The mouse uses rotational movement to generate electric power and operates using that electric power. The SoC consists of an RF transmitter and a microcontroller. Experimental results show that the RF transmitter block consumes 2.17 mW and the microcontroller block consumes 0.03 mW. The total power consumption is about 2.2 mW. Our target power consumption is achieved: 3 mW or less. That power consumption level is sufficiently low for the SoC to operate using the harvested electric power. Experimental results show that it can realize communication in a 1-m range.

Acknowledgment

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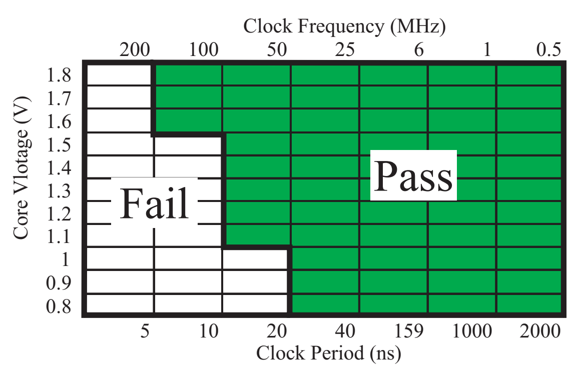

Fig. 11. Shmoo plot for the microcontroller