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Medication Management System Using Dual-Band In-/Out-body Wireless Communication

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Recently, the body area network (BAN) has been studied and widely developed. The system generally uses the 400 MHz and 2.4 GHz bands. Therefore, the antenna of the in-body sensor is large, and the miniaturization of an in-body sensor is difficult. When a high-frequency band such as a millimeter wave can be adopted, the sizes of the antenna and in-body sensor can be reduced by using an on-chip antenna. In this paper, a millimeter-size wireless device for the administration of medication is described, including the antenna for in-/out-body communication, wireless power transfer for small sensor chips, and wireless communication device.

1. Introduction

Recently, the application of wireless communication technology in the medical field has advanced[1] and applied to capsule endoscopy,[2] pacemakers,[3] hyperthermia, and so forth. Medication management is a vital process that involves overseeing a patient's prescribed medications to ensure correct dosage and achieve the desired outcome.[4,5] Medication management systems are important to prevent medication errors and missed doses. Several medication management systems have been proposed. In the pillbox-based management method,[6] pillboxes are equipped with sensors to control the timing and number of pills taken out. Moreover, tablet's information is transmitted when tablets are pushed out from pillbox. However, this system cannot verify if the medication has been taken or not after it has been removed from the box. In the digital medicine system,[7] sand-sized sensors are mixed with the medicine to be taken, and after reaching the stomach, the information of the taken medicine is transmitted to a patch-type detector on the body surface. Without a built-in battery, the chip contains trace amounts of magnesium and copper that react with gastric juice to supply power to the sensor. After use, the chip, which is mainly composed of carbon, is eliminated from the body, reducing side effects. However, the chip cannot communicate outside the body, so it is not possible to obtain information before the dose is taken and to prevent accidental dosing.

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We are considering a medication management system and devices with in-/out-body communication using ultrasmall wireless communication chips on tablets. Figure 1 shows the medication management system. A millimeter-sized chip is attached to a tablet. Before taking tablets, the chip transmits the type and number of medicines in the pill case. After the medication is taken, the identification (ID) and the number of medicines are identified by a sensor attached to the throat. The IDs are sent to a terminal to confirm that the medication was taken without forgetting. Since it is difficult to mount a battery on the chip, the communication chip is powered by a wireless power supply from the power supply coil under the pill case outside the body. In addition, the capacitor on the chip is charged to operate the circuit for a short period of time after the dose is taken. The proposed system is capable of communicating both inside and outside the body, and thus can prevent accidental dosing and missed doses. The system also enables an early detection of missed doses. In this paper, the components that can handle the ultrasmall wireless communication chip are introduced.

2. Wireless Communication Chip for Medication Management System

Figure 2 shows the block diagram of the wireless communication chip for digital medicine. A dual-band antenna, a low-power transmitter, and a wireless power transmission device are placed on the chip.

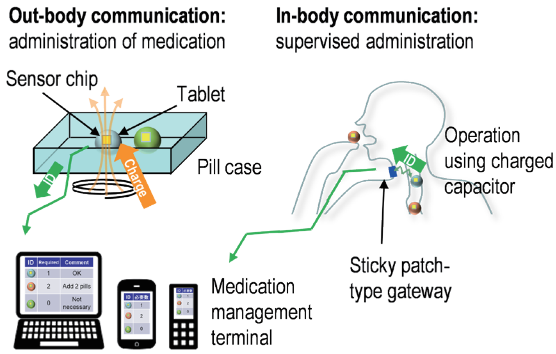

Fig. 1. (Color online) Medication management system using ultrasmall wireless communication chip.

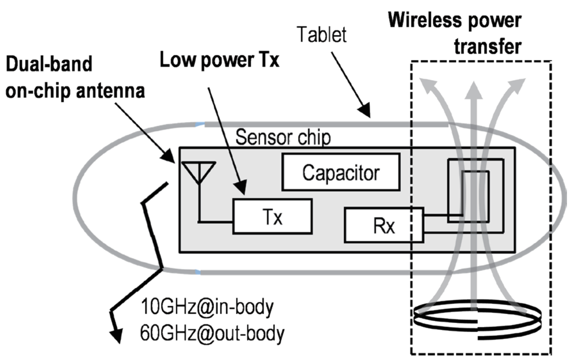

Fig. 2. Block diagram of wireless communication chip.

First, the antenna is important for in-/out- body wireless communication. In the case of in-body communication, the propagation loss of the human body is extremely high in the microwave frequency range,(8,9) and most of the developments have been made below 2.5 GHz.(2,7) When we consider wireless communication for tablets or pills, the antenna size is of great concern. At high frequencies, the antenna size decreases, but the radio propagation loss increases and the communication distance decreases short. On the other hand, at low frequencies, the loss is small, but the antenna size is large.(1) Communication under both out-body and in-body conditions is required to manage tablets or pills. Since a communication chip should be implemented or imprinted on small tablets or pills, the size should be less than a few mm square. Furthermore, a communication distance of at least 15 cm is required for communication from the chip inside the body to the body surface device.

Second, wireless power transmission technology is important. For devices that are to be taken to the human body, chemical batteries using heavy metals cannot be used for the protection of the human body. However, the medication management system also requires wireless communication within the body, and the communication chip must be powered. Wireless power transmission(10) is a technology that transmits power by means of radio waves, electric fields, and magnetic fields, enabling power to be supplied from outside the chip. The size of the coils and the overlap of the transmitting and receiving coils affect the characteristics of wireless power transmission by magnetic field coupling.(11) The power transmission efficiency decreases when small coils and a low overlap area are used.(12) To provide the power and charge the chip, high efficiency is needed with small coils on the chip. The size of coils is limited by that of the chip. In this paper, the chip coil size is limited to 1 mm.

Finally, low-power communication circuits are important. Generating high-frequency signals such as the 60 GHz signal is needed for the proposed wireless communication system. Many low-power communication circuits are proposed for millimeter-wave communication.(13,14) However, the power consumptions are mW class.(15–17) The size of the capacitor that charges the power is limited in the same way as that of the coil for wireless power transmission. To realize the proposed system, a 60 GHz communication chip with microwatt-class operation is required.

2.1 Dual-band antenna

To reduce the antenna size, a dual-band antenna for in-/out-body wireless communication(18) is introduced. Previous antennas for medical wireless devices are too large to put on medicines owing to the use of microwaves such as 2.45 GHz. To miniaturize the antenna, it is effective to use millimeter waves such as 60 GHz in air. The free space wavelength at 60 GHz is 5 mm, and considering the wavelength shortening effect on the chip, an antenna can be realized with a free space wavelength of about 1 mm. Since the human body is a high-loss medium, it is difficult to maintain the communication distance in the 60 GHz band and other millimeter waves. We proposed an antenna for both in-/out-body wireless communication using the resonance frequency drop caused by the high dielectric constant of the human body. In out-body wireless communication, we use the 60 GHz band to miniaturize the antenna. In the communication system, a lower frequency that has a smaller loss than the 60 GHz band is used with the same antenna. Figure 3 shows the simulated and measured return losses of the antenna under each (in-/out-body) condition. The return loss is the ratio of reflected energy to the energy input to the antenna, and the smaller it is, the more electrical energy is converted to electromagnetic energy at the antenna. Generally, −10 dB or less is considered to be a practical value for antennas. The antenna is formed by 18 umt copper wiring on a 1.6 mmt glass epoxy substrate. The Ansys HFSS is used for simulation and a vector network analyzer (R&S ZVA67) is used for measurement. Under the out-body (in air) condition, the antenna is matched in the 60 GHz band. Under the in-body (in water) condition, the matching center is shifted toward lower frequency (around 10–15 GHz) owing to the relatively high dielectric constant medium (i.e., water). This result indicates that this antenna can be used as a 60 GHz band under the out-body (in air) condition, whereas it would also be used around the 10–15 GHz range under the in-body (in water) condition. Since the absorption peak of water exists at a frequency above 15 GHz, it would be better to use the lowest frequency of around 10–15 GHz.

2.2 Wireless power transfer for chips on tablets in a pill case

2.2.1 Segment alternating power feeding for high transfer efficiency with small coil

To transmit power from the pill case to a small coil on the chip, a segment alternating arrayed power feeding coil is introduced.[20] For the proposed medicine management system, inductive coupling is applied, which is often used in the power transmission in a close situation. In the inductive coupling system, the coupling coefficient and Q-factor determine the power transfer efficiency. Since the transmitting coil under the pill case is larger than the receiving coil on the IC chip, the magnetic flux density at the center of the transmitting coil becomes relatively small and the power transfer efficiency becomes low. As shown in the EM simulation results, the magnetic flux density is the smallest at the center of the coil and becomes about 32-fold larger near the winding. When the smaller receiving coil is arranged inside the larger transmitting coil, the coupling coefficient is small. To increase the coupling coefficient between a large transmitting coil and an ultrasmall receiving coil, the transmitting coil is divided into some

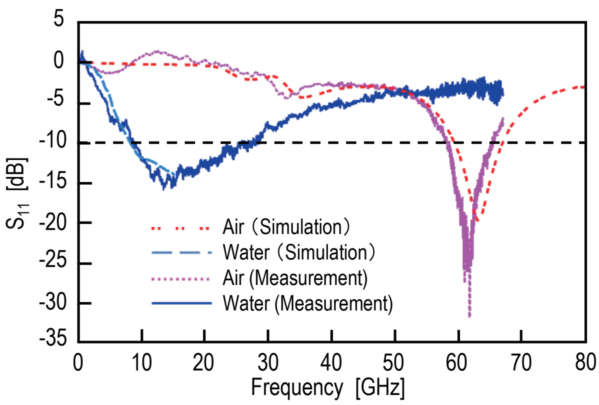

Fig. 3. (Color online) Simulated and measured return losses under out-body (in air) and in-body (in water) conditions.[19]

coils. The coils are powered by the alternate feeding of the adjacent coils as shown in Fig. 4. The distribution of the magnetic flux at time t, $t + 2$, ... is shown in Figs. 4(a) and 4(d), the distribution of the magnetic flux at $t + 1$, $t + 3$, … is shown in Figs. 4(b) and 4(e), and the time average distribution of the magnetic flux is shown in Figs. 4(c) and 4(f). The minimum magnetic flux of the four-segment alternating power feeding coil is about 1.2-fold that of the one-segment coil, and the minimum magnetic flux of the 16-segment coil is about 1.7-fold that of the one-segment coil. In addition, from Figs. 4(c) and 4(f), there is no region where the magnetic flux is null.

2.2.2 Result of segment alternating power feeding

Figure 5 shows the measurement results of the power transfer efficiency using a vector network analyzer (R&S ZVA67). The maximum efficiency was determined to be 0.1% at 617 MHz with the one-segment coil and 0.3% at 526 MHz with the four-segment alternating power feeding coil.

2.3 Low-power-consumption oscillator and transmitter

2.3.1 Design method for power-consumption reduction

To reduce the power consumption and chip size, a low-power-consumption oscillator and transmitter are introduced. To reduce the chip size, a large battery cannot be mounted. Since the power transfer efficiency between a large transmitting coil and an ultrasmall receiving coil is

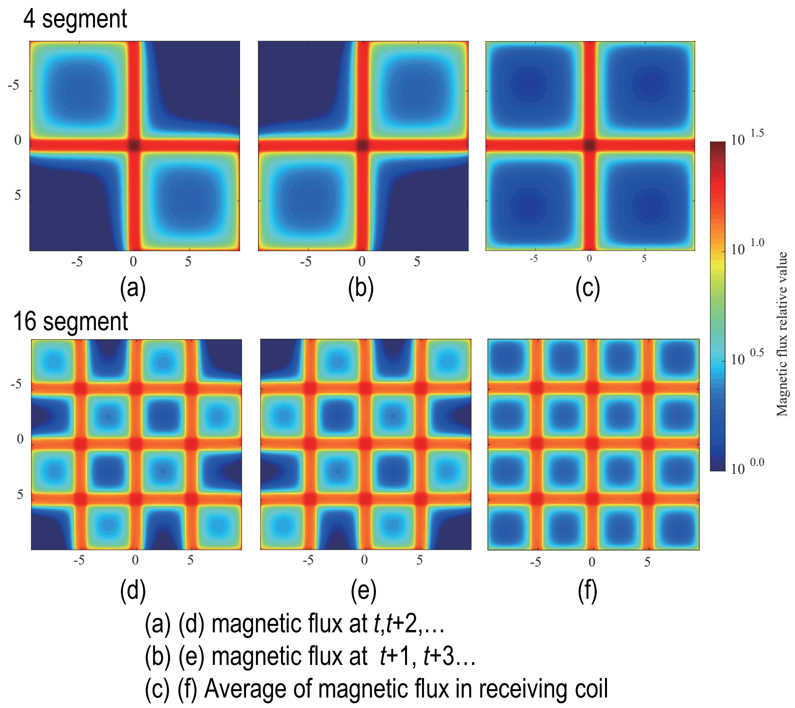

Fig. 4. (Color online) Magnetic flux distribution of segment alternating power feeding.

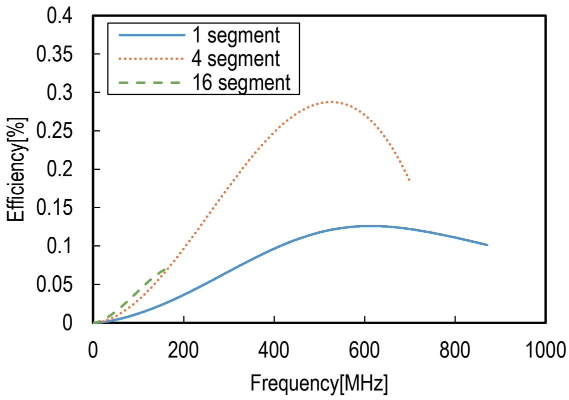

Fig. 5. (Color online) Measurement results of power transfer efficiency.

low, the power consumption of the transmitter should be reduced.(21) Figure 6(a) shows the schematic of the commonly used oscillator using cross-coupled MOSFETs, which is composed of looped two-stage amplifiers and revealed by a repeated MOSFET and a tank circuit as shown in Fig. 6(b). One block is composed of the MOSFET and tank circuit with iterative impedance. In this chain, the loss of the tank circuit is canceled by the gain of the MOSFET. The oscillation frequency is determined by the phase shift of the MOSFET and tank circuit. To decrease the power consumption of the oscillator, the efficiency of the MOSFET has to be maximized under the power consumption limitation. Figure 7 shows the gain and power consumption of the same-size common-source MOSFET with the sweeping of the gate and drain bias voltages. The gain and power consumption are calculated using a large signal scattering parameter and AC analysis at 60 GHz. Each line shows the contour of gain and power consumption. The upper side area is unacceptable because the power consumption is larger than the limitation. The lower side area is unacceptable because the gain is less than the limitation. Therefore, the middle area is the only acceptable area that meets the gain and power consumption limitation. This figure shows that when a point of dot is selected, the gain is larger than assumed and the loss of the tank circuit and power consumption meet the limitation. From the results, the transistor size and bias voltages are determined to achieve a low-power oscillator.

2.3.2 Result of fabricated 60 GHz wireless communication chip with 180 mW

The oscillator is fabricated in a standard 65 nm CMOS process. Figure 8 shows the measurement result of the spectrum and power consumptions. From the result of the oscillator with the bias voltages shown in Fig. 7, the oscillation frequency is 57.4 GHz with a power consumption of 130 mW.

Figure 9 shows the block diagram for a small chip size and a low-power-consumption amplitude shift keying (ASK) transmitter. The conventional ASK transmitter uses the continuance oscillator and external switch as the ASK modulator to achieve the high data rate. The buffer amplifier is employed to compensate for the loss of switch. The switch and amplifier increase the power consumption and chip size. The ASK transmitter based on the direct

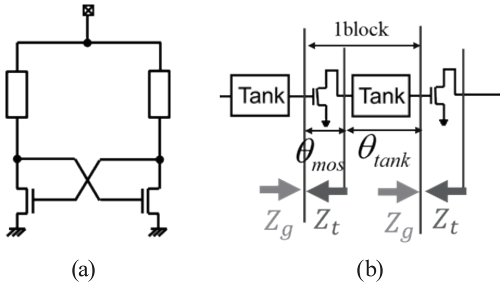

Fig. 6. Schematic of (a) oscillator topology and (b) analysis model as chain.

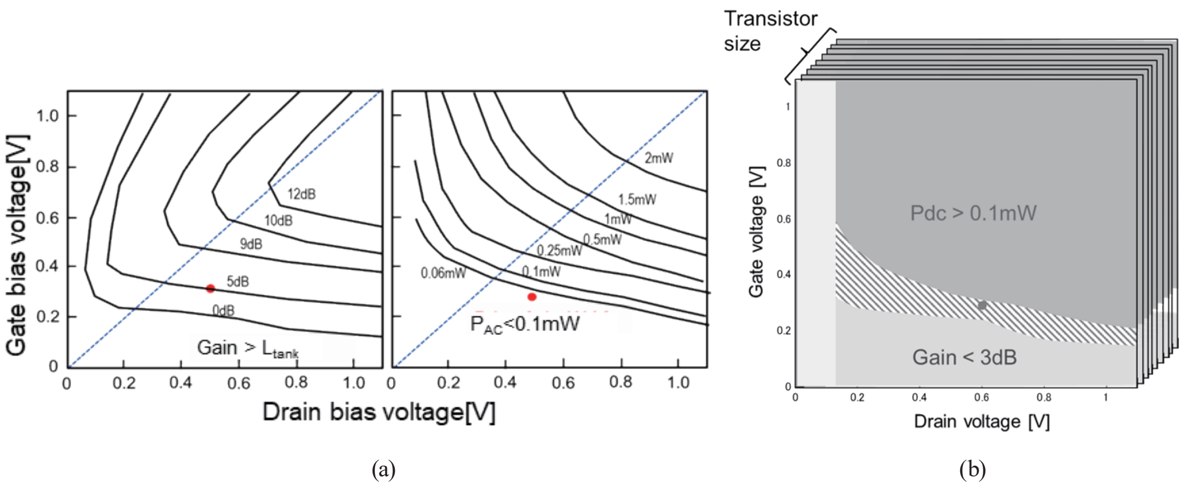

Fig. 7. (Color online) Gain and power consumption of MOSFET.

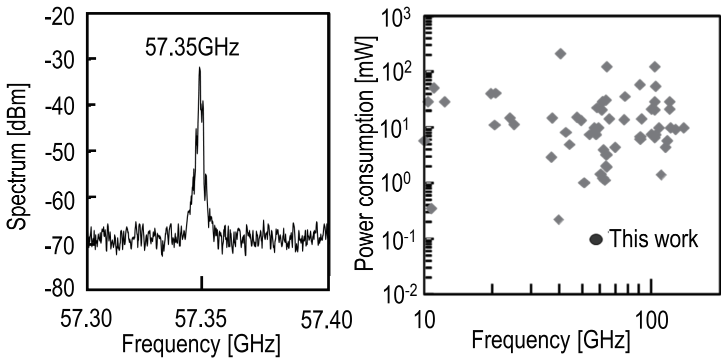

Fig. 8. Measurement result of the spectrum and power consumptions of reported CMOS millimeter-wave oscillators.

modulation shown in Fig. 9(b) can reduce the loss and power consumption. To reduce the power consumption and chip size, the external switch and buffer amplifier are removed. The oscillator directly turns on and off depending on the digital data to generate the ASK signal. The combined resonator and antenna can provide the radio wave from the oscillator directly and no buffer amplifier is required. The proposed transmitter has been fabricated by the standard 65 nm CMOS process. Figure 10 shows a chip micrograph. The core area is 1130 × 590 mm^2 with pads and output buffer.

Figure 11 show the measurement results of the (a) output voltage and (b) spectrum of the proposed ASK transmitter using the 50 Mbps $2^7 - 1$ PRBS signal. The power consumption is measured using a semiconductor parameter analyzer as a power source and is 180 mW. Figure 11(c) shows the on-off ratio of the transmitter and BER. The BER of 10^{-6} is achieved at 50 Mbps.

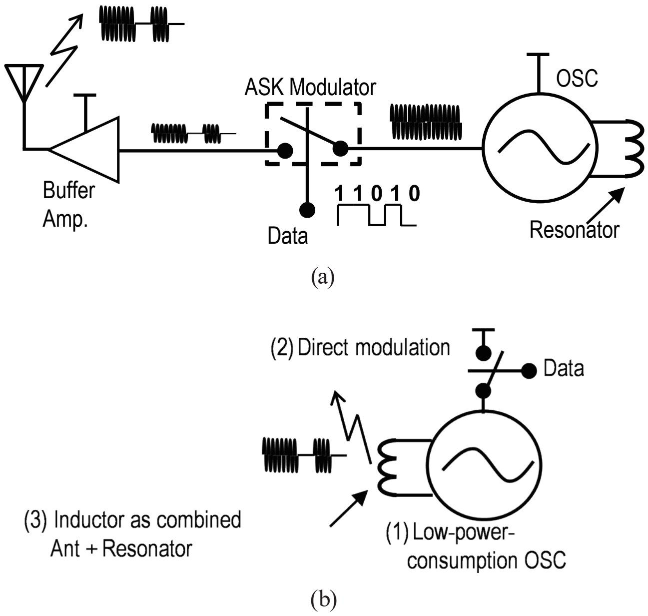

Fig. 9. Block diagram of ASK transmitter: (a) conventional and (b) proposed.

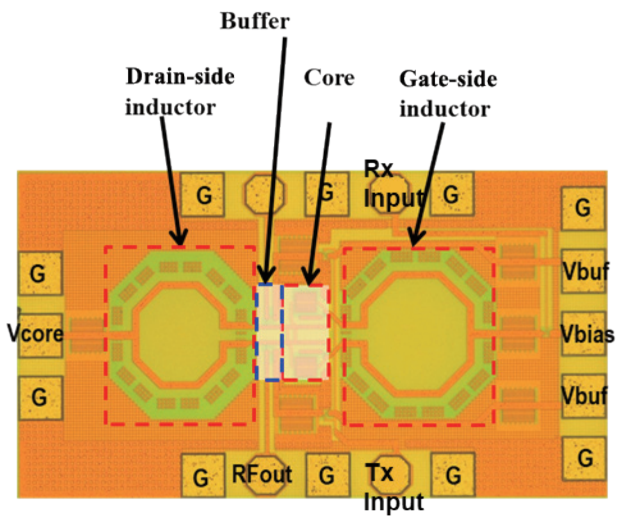

Fig. 10. (Color online) Chip micrograph of proposed ASK transmitter based on direct modulation oscillator.

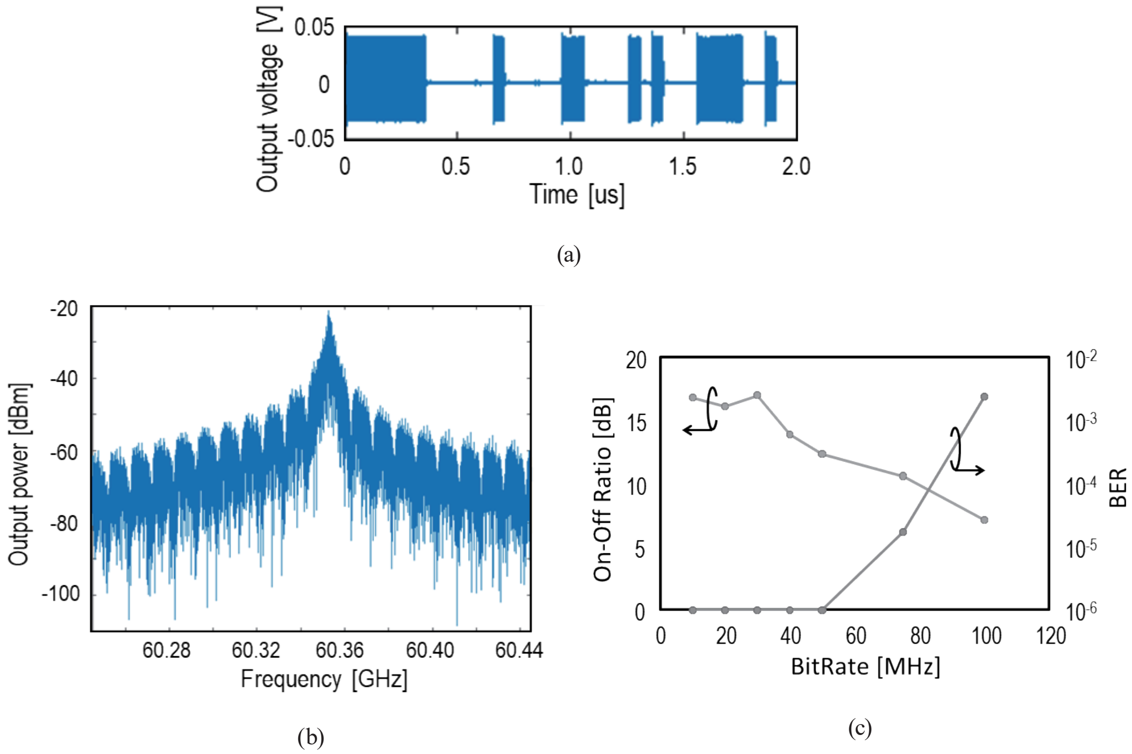

Fig. 11. (Color online) Measurement results of ASK modulated signal using proposed transmitter. (a) Time domain signal, (b) spectrum of antenna-out and probe-out, and (c) bitrate vs BER.

3. Conclusions

In this paper, a novel dual-band wireless communication system for medical usage is described. With the dual-band antenna for in-/out-body communication, wireless power transfers a large transmitting coil, and an ultrasmall receiving coil and a low-power millimeter-wave transmitter are introduced to achieve a novel medication management system with an ultrasmall wireless communication chip on tablets. The proposed system and devices are designed, and measurements using a human phantom model are performed. Total communication experiments in the actual body are an issue for the future.

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