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Magnetic Resonant Coupling Based Wireless Power Transfer System with In-Band Communication

Sun-Hee Kim, Yong-Seok Lim, and Seung-Jun Lee

***Abstract*—This paper presents a design of a wireless power transfer system based on magnetic resonant coupling technology with in-band wireless communication. To increase the transmission distance and compensate for the change in the effective capacitance due to the varying distance, the proposed system used a loop antenna with a selectable capacitor array. Because the increased transmission distance enables multiple charging, we added a communication protocol operated at the same frequency band to manage a network and control power circuits. In order to achieve the efficient bandwidth in both power transfer mode and communication mode, the S-parameters of the loop antennas are adjusted by switching a series resistor. Our test results showed that the loop antenna achieved a high Q factor in power transfer mode and enough passband in communication mode.**

***Index Terms*—Wireless power transfer, magnetic resonant loop antenna, in-band communication, Q-factor**

I. INTRODUCTION

Wireless power transfer technology enables various electronic devices, such as mobile phones, game controllers, laptop computers, mobile robots, and implantable devices, to be charged without connectors or cables, which is more convenient and environment-friendly [1, 2]. Inductive coupling and resonant coupling have been two main methods for wireless power transfer [3].

An inductively coupled power transfer system has a pair of coupled coils. At the transmitting side, an alternating current flows through a coil, generating a magnetic field. A receiving coil, which is close enough to the primary coil, picks up the field and generates a current to save power. According to previous studies, the effective operating range is usually less than 30 % of the diameter of coils [4]. To communicate between power transmitters and power receivers, the systems generally use load modulation because they are constructed on the same principle as inductive coupling [5].

A magnetic resonant coupling system uses a pair of coupled coils with additional capacitance, which makes the transmitter and the receiver have the same resonant frequency. It enables a highly efficient energy transmission over a longer distance compared to inductively coupled schemes [2]. In addition, an expanded operating range from centimeters to several meters allows more than two devices to be charged at the same time. Therefore these systems require a communication protocol not only for identifying devices but for networking and control. Communication protocols in wireless power transfer systems, however, have hardly been discussed in previous studies [6-8].

In this work, we propose a wireless communication and wireless power transceiver system based on magnetic resonant coupling. The same frequency band and loop antenna is shared for power transmission and data communication. Section II shows the architecture of the proposed system. Section III and IV and V describe the

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Department of Electronics Engineering , Ewha Womans Univ.
E-mail : slee@ewha.ac.kr

system implementation and the measurement results, respectively. Finally, Section V gives the conclusion.

II. System Architecture

1. In-Band Communication

We adopted Magnetic Field Area Network (MFAN) as our wireless communication method for sharing the same low frequency band and antenna in power transfer mode. MFAN, one of Korean Industrial Standards [9, 10] that has been adopted as an International Standard [11], supports BPSK requiring a bandwidth of 8 KHz centered at the carrier frequency of 128 KHz. It composes of a network based on star topology. One coordinator in a network is responsible for initiating and managing other devices or nodes. A TDMA-based superframe consists of three frames: request, response, and inactive. A network is set up during the request frame and data is exchanged during the response frame. There is no traffic in the inactive frame.

To apply the standard to a power transfer system, we added some functions that are compatible with the original protocol. After a power transmitting system establishes the network as a coordinator, it decides and transmits parameters, such as when the inactive frame starts and how many sub-slots it comprises of, to each node. During the inactive frame, the coordinator transmits power to all or selected nodes. Fig. 1 shows a proposed superframe structure.

Signals for the system are required to be continuous waves for transferring power effectively. MFAN physical layer packet is composed of preamble, header, and variable length payload. After adding error check sequences, the packet is encoded using Manchester code. When the system operates in power transfer mode, the coordinator sends only data 0 regardless of the packet structure or Manchester scheme. A block diagram for in-band communication is shown in Fig. 2.

2. Power Transmitting System

A power transmitting system, or a coordinator, consists of a system controller, a MFAN modem, amplifying circuits, resonant matching circuits, and a loop antenna. A system controller includes a MFAN MAC and schedules networking and transferring power.

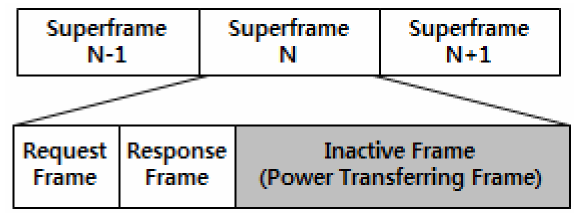


Fig. 1. Proposed superframe structure.

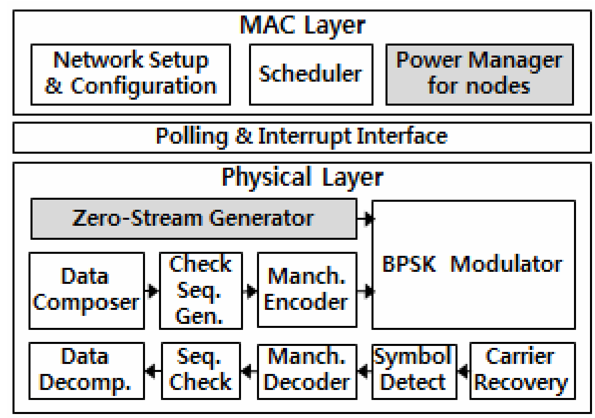


Fig. 2. Block diagram for in-band communication.

A MFAN modem is composed of a digital part and an analog part. As stated above, the digital part generates and decomposes the physical layer packets. The analog part for transmitting consists of a DAC and an amplifier that are also used in power transfer mode. The receiving analog part is made up of a LNA, a LPF and an ADC.

An amplifier is varied from 1 W to 10 W at the scale of 0.5 dB depending on the operation mode, either power transfer mode or communication mode, or the distance between a coordinator and a receiving node.

Resonant matching circuits consist of switches and a capacitor array in parallel with a loop antenna. Because the effective capacitance is varied with the distance between a coordinator and a receiving node, capacitors are configured by controllable switches before power transmission. Fig. 3 shows a block diagram of analog circuits for a power transmitting system.

In this system, we have to consider the Q factor for the antenna not only for efficient energy transmission but also for robust communication. Generally wireless power transfer systems make the Q factor as high as possible. But this means that the bandwidth becomes too narrow for communication.

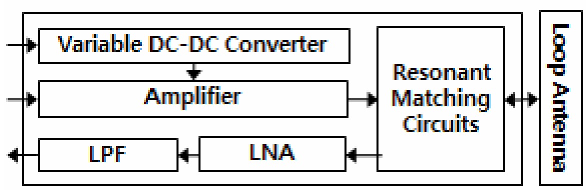


Fig. 3. Analog circuit block diagram for power transmitting system.

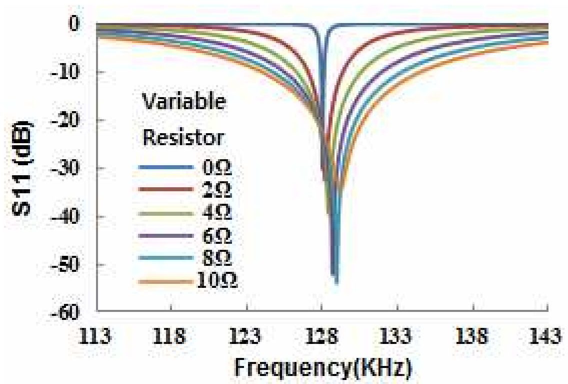


Fig. 4. Simulation results: S11 of an antenna for power transmitting system with a variable resistor in series with a coil (inductance of a coil : 102.25 uH, capacitance of a matching circuit : 15.12 nF , parasitic resistance : 0.185 ohm).

Q factor is defined by the following equation,

$$Q = \frac{2\pi f L}{R} \tag{1}$$

where f represents the operating frequency, L the inductance of a loop antenna, and R the resistance in series. As shown in Fig. 4, S11 is changed according to R when the inductance of a loop is 102.25 μH, the capacitance of matching circuits is 15.12 nF, and the parasitic resistance is 0.185 ohm. As R increases, the bandwidth becomes wider, but, the loss becomes greater. Therefore a series resistor is switched on or off according to the operating mode.

3. Power Receiving System

A power receiving system, or a node, consists of a system controller, a MFAN modem, power conversion circuits, resonant matching circuits, and a loop antenna. Fig. 5 shows a block diagram of analog circuits for the power receiving system

A captured magnetic field at the antenna passes

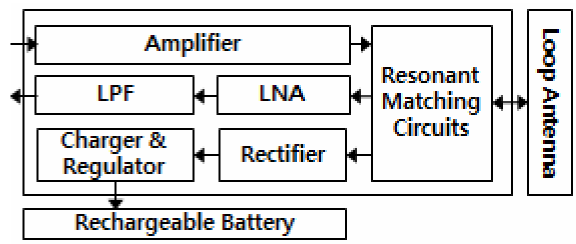


Fig. 5. Block diagram of analog circuits for the power receiving system.

through a rectifier, a regulator and a charger, and then the energy is stored in a rechargeable battery. In power transfer mode, the signal is much larger than the one in communication mode. So we use power devices for power conversion, and a protector in the path for communication. And we added a switch between the protector and the antenna to disconnect them during power transfer mode. The switch is automatically controlled by a system controller.

To make the size of a node small, its resonant matching circuits use only one capacitor, and the compensation for the varied resonant frequency is made on the coordinator side.

III. IMPLEMENTATION

We implemented a SoC, shown in Fig. 6, for the proposed system using 0.18 μm CMOS process. As shown in Fig. 7, the chip consists of a microprocessor, a ROM for boot code, an SRAM for data and program, digital parts of modem, ADCs, PLL, and various interfaces such as UART and SPI for controlling the analog parts.

Fig. 8(a) shows a power transmitting system board including a SoC and analog circuits in Fig. 3, and a large loop antenna. The supply voltage of transmitting analog circuits is adjusted by a variable resistor at feedback path of a DC-DC converter, R_F in Fig. 8(b). The amplifier consists of four MOSFETs (N1, N2, N3, and N4) as a full-bridge inverter. N1 and N4 are switched together with a less than 50% duty cycle. The switching time for N2 and N3 is then 180° phase-shifted relative to the time for N1 and N4. Generated square signals are filtered with capacitors of matching circuits and inductors of the antenna. Before transmitting power or data packets, the parallel capacitor array (Cp_t) and the series resistor

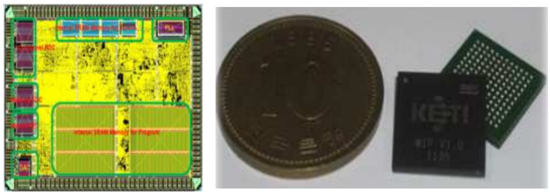


Fig. 6. SoC layout and chips.

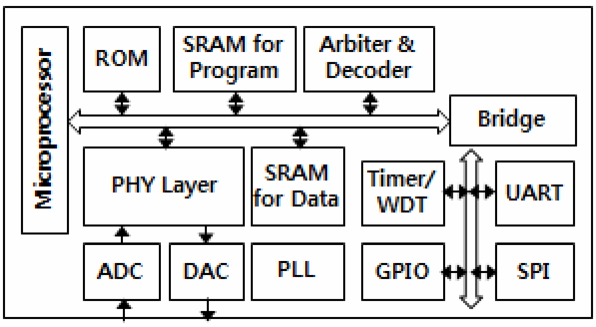


Fig. 7. Block diagram of SoC.

(Rs_t) are configured to match the resonant frequency and to change the Q-factor.

Fig. 8(c) illustrates a power receiving system board with a SoC, analog circuits in Fig. 6, and a battery and a small loop antenna. In the power receiving circuits in Fig. 8(d), a full-bridge rectifier is used. Unlike the matching circuits of the transmitter, the parallel capacitor (Cp_r) is fixed.

Table 1 summarizes the parameters of the loop antennas. We used a resistor of 10 ohms based on the simulation result to change the Q factor. When the system operates in power transmission mode, the resistor is bypassed and only the parasitic resistance affects the Q factor. When in communication mode, the resistor is connected and the Q factor is reduced because of increased resistance.

IV. Measurement Results

Fig. 9 presents the test environment. We used one transmitting system and one receiving node. The receiving antenna was located 20 cm away from the transmitting antenna. Initially, the transmitting system started to build a network. After exchanging power-transfer parameters, they operated in power transmission mode.

We measured amplifier output waveforms of the

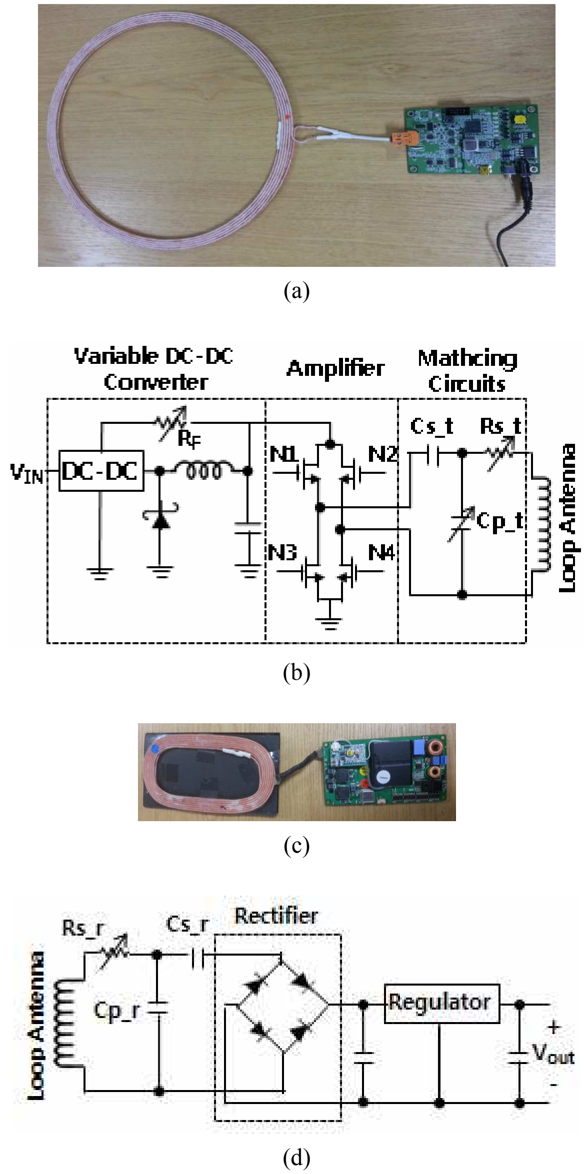
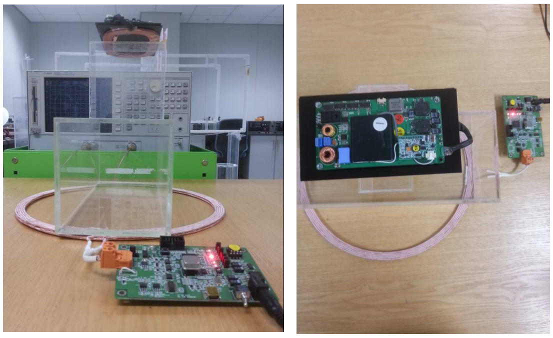


Fig. 8. Implemented systems (a) power transmitting system board including a SoC and analog circuits, and a large loop antenna, (b) transmitting circuits, (c) power receiving system board with a SoC, analog circuits, and a battery and a small loop antenna, (d) power receiving circuits.

Table 1. Parameters of loop antennas

		antenna of power transmitting system	antenna of power receiving system
Size (mm)		310 (diameter)	140 x 75
Inductance (uH)		102.25	31.394
Q - Factor	On power transmission ($R=R_{pararstic}$)	444 (0.185Ω)	252 (0.1Ω)
	On communication ($R=R_{pararstic}+R_{series}$)	8.1 (10.185Ω)	2.5 (10.1Ω)



(a) (b)

Fig. 9. Test environments (a) side view, (b) top view.

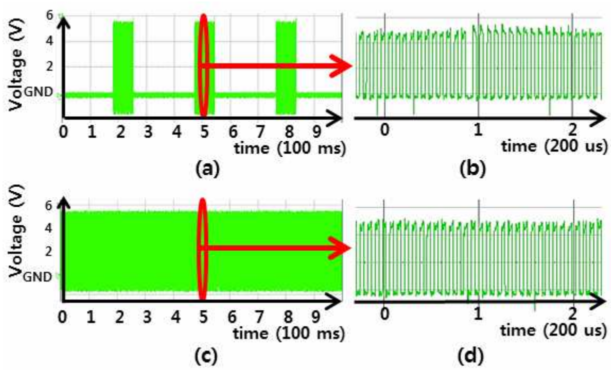
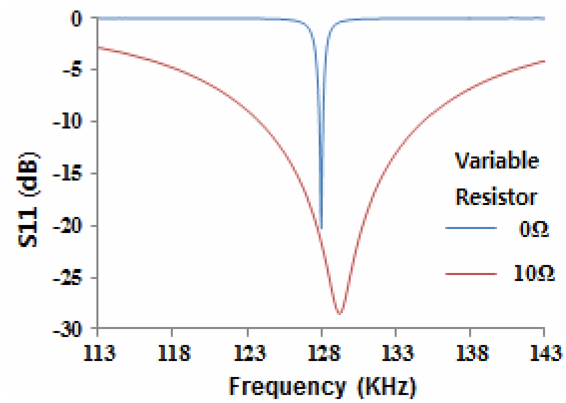


Fig. 10. Measured amplifier output waveforms of a power transferring system (a) waveform at a response frame, (b) an enlarged display of (a), (c) waveform at an inactive frame, (d) an enlarged display of (c), (oscilloscope setting : 2 mV/div, 100 ms/div @ (a), (c), 2 mV/div, 200 us/div @ (b),(d)).

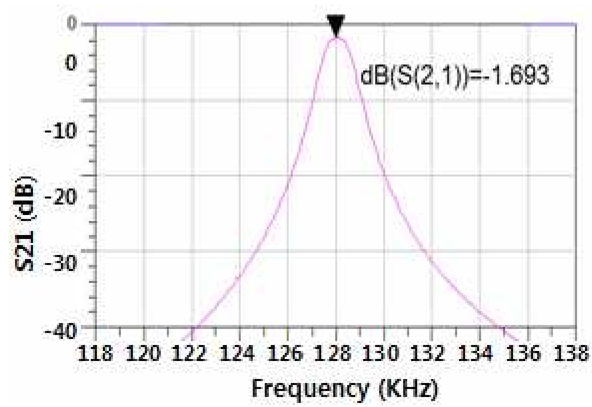
power transmitting system. Fig. 10(a) shows the measured waveform using an oscilloscope for the response frame, in which three data packets are transmitted. As is shown in Fig. 10(b), BPSK-modulated packets have moments in which the phase is changed. During the inactive frame, however, the phase of the signal is maintained as shown in Fig. 10(c) and Fig. 10(d) because data is unchanged during the power transfer.

Fig. 11 shows S11 of a large loop antenna measured according to a variable resistor, S21 measured at the distance of 20 cm between two loop antennas using a network analyzer and power transmission efficiency (η). We observed that -10 dB of S11 at passband was obtained. The power transmission efficiency between antennas was about 68% (S21=-1.693 dB) at 20 cm as shown in the following equation [12, 13].

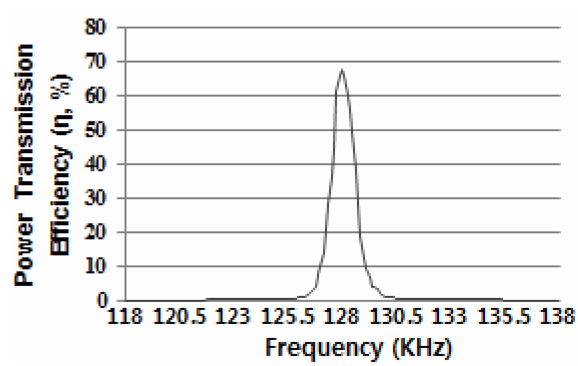
$$\eta = |S_{21}|^2 \times 100\% \qquad (2)$$



(a)



(b)



(c)

Fig. 11. Measured S-Parameters (a) S11 of a large loop antenna, (b) S21 at 20 cm, (c) power transmission efficiency (η) between antennas.

And the full system efficiency was about 40% from the DC power output of the amplifier at transmitter to DC output of the rectifier at receiver. By these experiments, we confirmed that our systems developed a network and transferred energy.

V. CONCLUSIONS

A wireless power transfer system based on magnetic resonant coupling technology was implemented with an in-band communication method, MFAN. To increase a transmission distance and improve energy efficiency, we made a resonant loop antenna with variable capacitor array. To compensate for the change in the effective capacitance due to the varying distance, a power transmitting system used a selectable capacitor array and a power receiving system used a fixed capacitor for size reduction. By switching a series resistor, the loop antenna can have a high Q-factor in power transfer mode and an enough passband at communication mode. A custom-designed SoC was implemented for the proposed system.

Experiments showed the wireless power transmitting system and the wireless power receiving system successfully formed a network, communicated with each other, and transferred power wirelessly with transmission efficiency of about 40% at 20 cm.

ACKNOWLEDGMENTS

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Sun-Hee Kim received the B.S. and M.S. degrees in Electronics Engineering from Ewha Womans University, Seoul, Korea, in 2000 and 2002, respectively. From 2002 to 2005, she worked at Electronics and Telecommunications Research Institute. From 2005 to 2012, she worked at Korea Electronics Technology Institute. She is currently working toward the Ph.D. degree at the same university. Her interests include system level low-power design and wireless power transfer technology.

Yong-Seok Lim received the B.S. and M.S. degrees in Electrical Engineering from Korea University, Seoul, Korea, in 2001, and 2003, respectively. From 2003 to 2005, he worked at Samsung Electro-Mechanics. Since 2007, he has been a senior researcher of Wireless Platform Research Center of the Korea Electronics Technology Institute. And he is currently working toward the Ph.D. degree at the same university. His interests include wireless and network SOC system architecture and wireless power transfer.

Seung-Jun Lee received the B.S. degree in Electronics Engineering from Seoul National University, Seoul, Korea, in 1986, and the M.S. and Ph.D degrees in Electrical Engineering and Computer Science from the University of California at Berkeley, in 1989 and 1993, respectively. From 1993 to 1998 he worked at Hyundai Electronics Industries. Since 1999, he has been with the Department of Electronics Engineering at Ewha Womans University, Seoul. His research interests include the design of digital circuits, wireless communication system, and system level design methodology