Near-Field Dual-Use Antenna for Magnetic-Field based Communication and Electrical-Field based Distance Sensing in mm^3-Class Sensor Node

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***Abstract*—This paper proposes a mm^3-class dual-use near-field antenna that can be used for both magnetic-field based communication and electrical-field based distance sensing. The proposed antenna consists of two spiral coils, and they are used as a coil antenna in communication mode and signal electrodes in distance sensing mode. We evaluated the performance of the communication mode with a prototype antenna. The measured S21 is -8.3 dB to -45.1 dB in the range from 6 mm to 24 mm, which is highly correlated to 3D full-wave electromagnetic simulation. With this antenna, we performed BER evaluation with commercial transceiver boards showing that the proposed antenna could be used for ASK/OOK signaling. We also confirmed that the proposed antenna could be used for cm-scale node-to-node distance sensing through capacitive coupling.**

I. Introduction

With aggressive VLSI technology advancement, signal processing and computation in a small volume like cubic-millimeter is becoming possible [1], [2]. Such small volume computation can be embedded anywhere, which can contribute to new human-computer interaction in IoT (Internet of Things) era. On the other hand, for implementing applications, the computing device needs to receive power supply, sense signals and transmit processed signals. These power supply, sensing and signal transmission are all challenging since the volume is very small and the numbers and performance of electrodes and antennas are highly limited.

As an application of small volume computation, we have proposed a concept named “iClay” (Fig. 1) [3]. The iClay system is supposed to provide instant real-time 3D modeling with the clay, in which small sensor nodes are embedded. Through the sensor network consisting of sensor nodes and a host computer, the distance information between sensor nodes is collected and the clay shape is reconstructed based on the distance information. For actuating this particular application of iClay, we have to establish wireless power supply, wireless communication, distance sensing to adjacent sensor nodes, and clay shape reconstruction. For shape reconstruction, a cross-entropy based node localization method is developed and its parallel computation efficiency is presented in [4]. Ref. [5] demonstrated wireless power transfer of 450 μW to a 50mm^3 node, where the majority of the volume consists of helical coil resonator. Ref. [6] discusses the coil design at the power transmitter side and designs a wireless power transfer system.

This paper focuses on the wireless communication and distance sensing, and proposes a tiny dual-use antenna that can be used for both magnetic-field based communication and electrical-field based distance sensing. We perform full-wave 3D electromagnetic simulations to show the feasibility of the dual-use antenna. Also, we make prototypes of the proposed antenna, measure their performance with network analyzer and confirm wireless data transmission with commercial transceiver boards.

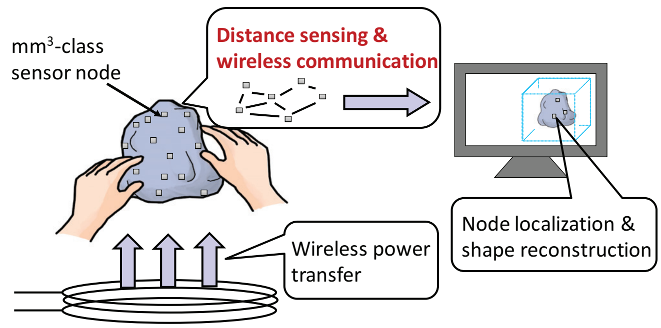

Fig. 1. iClay system.

TABLE I. Existing distance sensing methods.

Method	Principle	Problem
Wireless TOA/TDOA	Prop. time	Proximity sensing difficult
Wireless RSSI	Attenuation	Proximity sensing difficult
Light	Reflection	Not propagate in clay
Ultrasonic	Reflection	Weak to obstacles
Eddy current	Mag. field	Strong directivity
Cap. coupling	Elec. field	Suitable for iClay system

II. Distance sensing and Wireless communication

A. Distance sensing

In the iClay system, each sensor node is expected to have distance sensing ability for all the directions in the clay. TABLE I lists existing distance sensing methods. Time of arrival (TOA), time difference of arrival (TDOA), and received signal strength indication (RSSI) are common methods for distance sensing in wireless sensor networks. However, these methods cannot be used for proximity sensing because these methods require highly accurate time synchronization and signal attenuation in mm-scale distance is too small. Distance sensing based on light and ultrasonic cannot work in the medium of clay. Capacitive coupling based sensing is more promising than eddy current based one since the directivity of electrical field is weaker than that of magnetic field.

Ref. [7] shows that capacitive coupling is capable of up to 10mm distance sensing. Fig. 2 illustrates the capacitive coupling based distance sensing proposed in [7]. Two electrodes at each node compose a current loop through coupling capacitances, where some capacitive couplings between those electrodes are omitted in the figure. The transmitter (TX)

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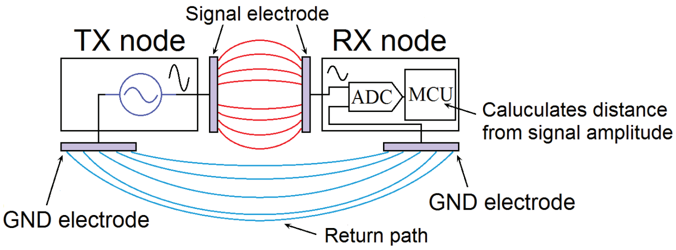

Fig. 2. Distance sensing based on capacitive coupling.

node injects a signal to the signal electrode, and the receiver (RX) node receives the signal and digitizes the amplitude of the received signal. The capacitance value is sensitive to the distance in such a proximity range, and hence the signal amplitude varies depending on the distance. Then, the distance is calculated from the amplitude in the RX or in the host computer.

B. Wireless communication

Each sensor node also needs to perform wireless communication to send node-to-node distance data to a host computer. Generally, helical coil antenna has higher gain than spiral coil antenna. However, helical coil is not suitable for iClay sensor node since wireless power transmission [5] already uses one helical coil resonator and mm^3-class sensor node cannot accommodate two helical coils. Therefore, spiral coil antenna needs to be studied.

There are two possible communication schemes; carrier wave based communication and pulse based communication. Pulse-based transmission through inductive coupling is presented in [9], where TX node injects pulse signals to the spiral coil antenna and RX node senses the transmitted pulses with the spiral coil antenna. Ref. [9] demonstrated high data rate communication with tiny spiral coil antenna. However, pulse-based signal transmission with inductive coupling cannot be used for iClay system since the antenna is always exposed to high intensity electromagnetic field for wireless power transfer, and hence it is difficult for RX node to sense pulse signals. Therefore, we need to choose carrier wave based communication and consequently design an antenna whose resonant frequency is adjusted to the carrier frequency.

III. Proposed Antenna Structure

When implementing a sensor node for iClay, one of the biggest difficulties is to accommodate all the functionalities in a small volume. A helical coil resonator for wireless power transfer [5] occupies a large portion of the volume, and hence two electrodes for distance sensing and the spiral coil antenna for communication must be accommodated in the remaining small space. To fulfill this requirement, this paper proposes a dual-use antenna shown in Fig. 3, where the antenna consists of two spiral coils facing each other and two capacitors C_1 and C_k. The proposed antenna provides two functional modes by selectively enabling one of voltage sources; wireless communication mode and distance sensing mode.

In wireless communication mode, the voltage source V_c is enabled and V_d is disenabled, where the disenabled voltage source is in high impedance (Hi-Z) state. The capacitance C_1 is used to cancel the reactance component and attain impedance matching. In this mode, two spiral coils are electrically disconnected each other from DC point of view, and the left coil driven by the voltage source generates magnetic field. The right coil, on the other hand, receives the power from the magnetic field and radiates the resonant radio wave, where the right coil and C_k compose an LC resonant circuit. Note that if the resonant frequency of the left coil is identical to that of the right one, their magnetic coupling may become stronger [10] and the communication range could improve. On the other hand, we observed that the maximum improvement was 0.6dB in the simulation and hence the capacitance C_1 is solely used for impedance matching and another capacitance for tuning resonant frequency is not included.

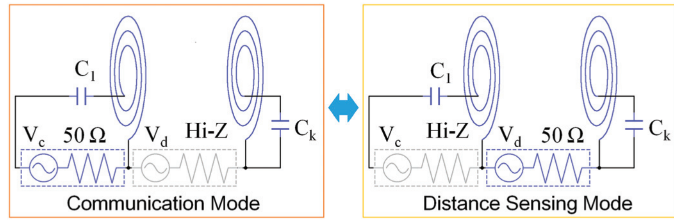

Fig. 3. Proposed dual-use antenna providing two function modes.

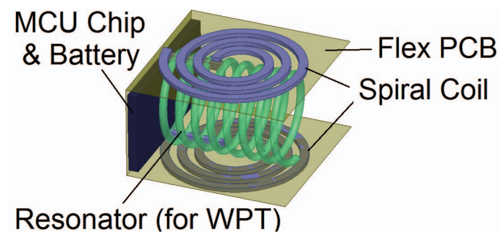

Fig. 4. Accommodating helical coil resonator for wireless power transfer and proposed dual-use antenna in a sensor node.

In distance sensing mode, voltage source V_d is enabled and two spiral coils are electrically connected. In this mode, there is no DC loop and these spiral coils are supposed to behave as disc electrodes. By using these two spiral coils as SIG and GND electrodes in Fig. 2, the proposed antenna is expected to sense distance between adjacent nodes.

The proposed dual-use antenna can be accommodated in sensor node consistently with the helical coil resonator as depicted in Fig. 4. The proposed antenna is printed on a flexible PCB and connected to transmitters mounted on the flexible PCB.

IV. Evaluation

To confirm the effectiveness of the proposed dual-use antenna, we evaluate the performance in communication mode and distance sensing mode. We make prototype antennas, measure their characteristics, and confirm communication with commercial transceiver boards. We also simulate S21 characteristics with a 3D full-wave electromagnetic simulator (ANSYS HFSS) and verify hardware-model correlation.

A. Setup

Fig. 5 shows the prototype antenna, where the diameter of the coil is 4.4mm and the number of turns is 3. The

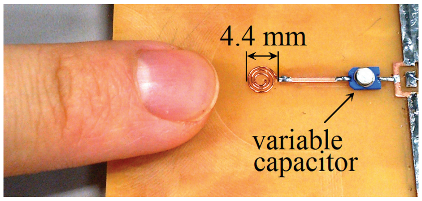

Fig. 5. Prototype antenna.

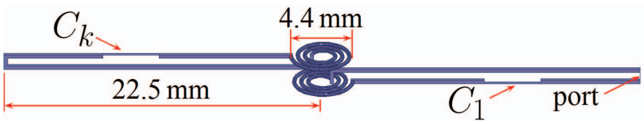

Fig. 6. Simulation model corresponding to prototype of Fig. 5.

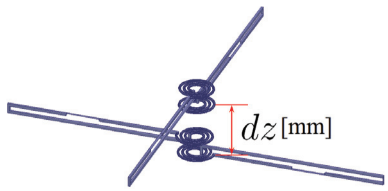

Fig. 7. S21 simulation model with lead wire.

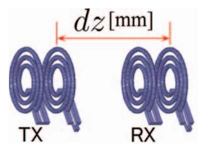

Fig. 8. S21 simulation model w/o lead wire.

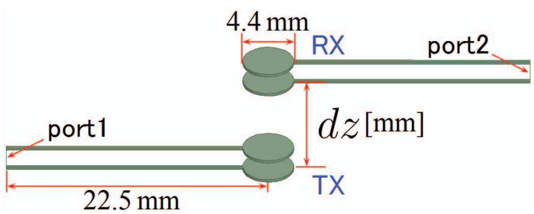

Fig. 9. Simulation model with disc electrodes in distance sensing mode.

spiral coil is made of polyurethane enameled copper wire and the wire diameter is 0.26mm. The distance between the two coils is 2mm. A small blue electronic component is a variable capacitor that adjusts the resonant frequency or the characteristic impedance. This time, the resonant frequency is set to 433MHz. We measure S11 and S21 characteristics of this prototype antenna using a network analyzer (Agilent Technologies, E5071C) with TRL calibration method.

Next, we explain simulation models. Fig. 6 shows the simulation model that is compatible with Fig. 5. When we evaluate S21 characteristic, we locate two nodes, where one is TX node and the other is RX node, facing each other and change node-to-node distance dz as depicted in Fig. 7. For evaluating the true performance of the antenna without the lead wire to the variable capacitor, we also evaluate the simulation model of Fig. 8. As another alternative, we consider the antenna shown in Fig. 10, where a single coil is used with two tuning capacitors. The capacitors are used for adjusting resonant frequency and performing impedance matching. If the proposed antenna has poorer performance, the power transmission from the left coil to the right coil in Fig. 3 causes power loss.

In distance sensing mode, the sensor node uses each spiral antenna as a disc electrode. Therefore, we need to evaluate the performance difference between the spiral coil and disc electrode. Fig. 9 shows the model of disc electrode for comparison.

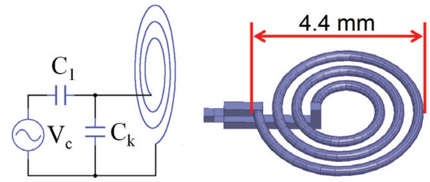

Fig. 10. Antenna with a coil and two capacitors and its simulation model.

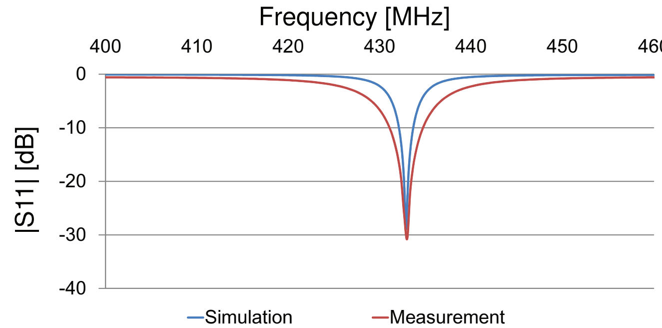

Fig. 11. Measured and simulated S11.

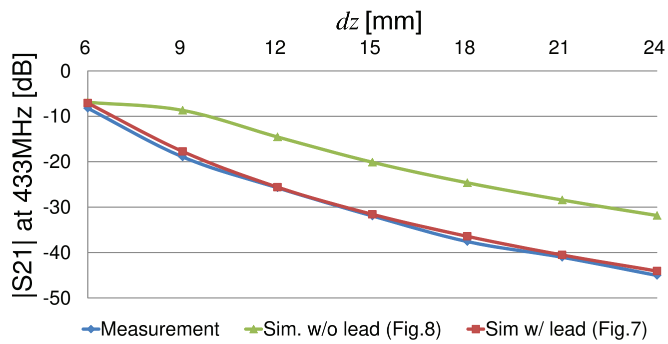

Fig. 12. Measured and simulated S21 results in communication mode.

B. Results in communication mode

Fig. 11 shows the measured and simulated S11 characteristics. In both cases, S11 is lower than -28 db at the resonant frequency of 433MHz. This indicates impedance matching is well attained.

Fig. 12 shows the measured and simulated S21 characteristics. We can see that the measurement result and the simulation result of Fig. 7 are well correlated, which validates our simulation setup and corresponding simulation results. In addition, this result indicates that the loss originating from the parasitic resistance of the variable capacitor is not significant since the ideal capacitor is considered in the simulation. On the other hand, we observe that the lead wire plays an important role for S21 characteristics. The simulation model with lead wire (Fig. 7) attains lower S21 than that without lead wire (Fig. 8). For simulating antenna, we need to model the entire structure of the antenna.

Next. we show the comparison result between the proposed antenna with two spirals and the alternative with one spiral in Fig. 10. Fig. 13 shows the simulated S21 magnitude. We can see these two antennas attain almost identical S21 performance, which indicates that the power injected to the left coil is well transferred to the right coil and radiated from

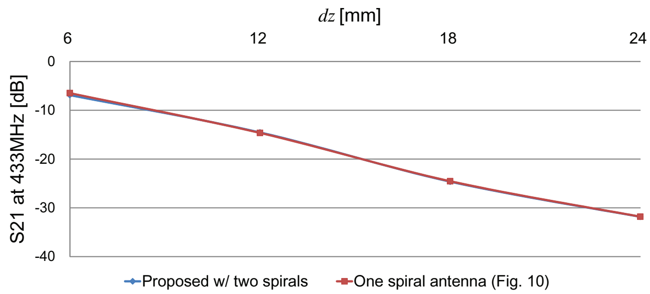

Fig. 13. S21 comparison between proposed antenna and Fig. 10.

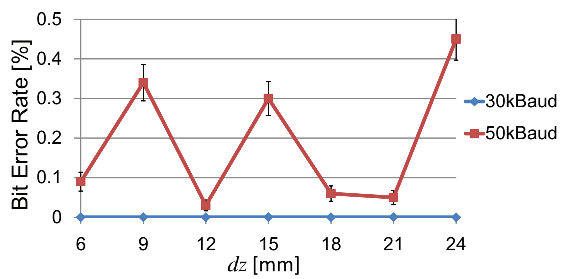

Fig. 14. Measured BER of ASK/OOK.

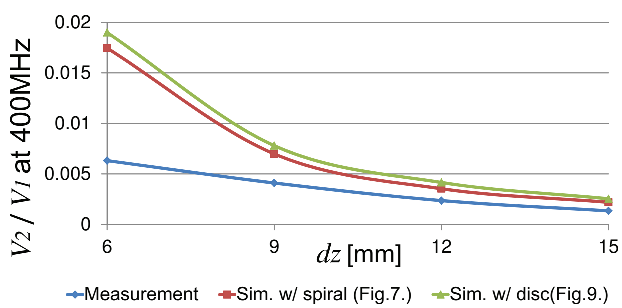

Fig. 15. Measured and simulated V_2/V_1 in distance sensing mode.

the right coil in the proposed antenna.

To verify that the proposed antenna can be used for carrier wave based communication, we performed a communication experiment with commercial transceivers and the prototype antennas. As shown Fig. 11, the proposed antenna has a narrower bandwidth since it uses resonance. In this case, frequency modulation based communication is not suitable. Instead, amplitude modulation based communication is desirable. We therefore selected ASK/OOK for this setup. We used CC1110 and CC1111 development kit of TI for this experiment. We set the carrier frequency of the transceivers to 433MHz and transmitting power to -30dBm, and we evaluated bit error rate (BER). Fig. 14 shows the measured BER, where the error bar is the standard deviation. When we set communication baud rate to 30 kBaud, no bit errors were found. Even when we set baud rate to 50 kBuad, BER was at most 0.45%. This result demonstrates the proposed antenna can be used for ASK/OOK modulation based wireless communication.

C. Results in distance sensing mode

Fig. 15 shows the simulated and measured V_2/V_1 ratio of the proposed antenna where the V_1[V] is the signal amplitude injected to TX node and V_2[V] is the measured amplitude of signal in RX node. V_2/V_1 is calculated based on the impedance matrix converted from the measured/simulated S parameters. We can see that the spiral electrodes (Fig. 7) have similar V_2/V_1 to the disc electrodes (Fig. 9). This indicates that spiral coils can be regarded as discs in distance sensing mode and the proposed dual-usage is validated. On the other hand, there is a gap between the measured V_2/V_1 and simulated V_2/V_1, and the measured V_2/V_1 is smaller than the simulated one. We need to study the root of cause of this gap.

V. Conclusion

This paper proposed a tiny dual-use antenna suitable for mm^3-class sensor node. The proposed antenna can be used for wireless communication and proximity distance sensing, which contributes to the small volume integration even with a helical coil resonator for wireless power transfer. The experiments with prototype antenna measurement and 3D electromagnetic simulation demonstrated that the proposed antenna was capable of cm-scale wireless communication. We also confirmed that the electrodes consisting of coils worked similar to the disc electrodes for distance sensing. Further feasibility investigation on distance sensing with peripheral circuits is one of our future works.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 15H01679. The authors thank Dr. Morimura and Dr. Kondo of NTT for technical discussions.

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