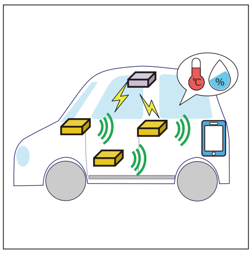

Wireless Power Transfer to Sensors within Vehicle Cabin

Toyohisa TAKANO*, Suguru YAMAGISHI, Ichirou KUWAYAMA, and Kenji ITOH

With the advancement of autonomous driving and vehicle electrification, the number of onboard sensors is expected to increase. Powering each sensor via wired connections can lead to increased costs and weight due to power and communication cables. This paper investigates wireless power transmission using a spatial transmission method to supply power to each sensor. We confirmed that a temperature sensor embedded in the headrest could operate at 30-second intervals using wireless power transmission at a transmission frequency of 920 MHz and a transmission power of 1W. In addition, we simulated the distribution of electric field intensity inside the vehicle cabin and confirmed that the electric field intensity required for the sensor to operate could be achieved in most areas of the cabin.

Keywords: wireless power transfer, rectenna, compact

1. Introduction

With the advancement of autonomous driving and vehicle electrification, it is desired to improve the comfortability of the cabin space. In order to improve the comfortability, it is necessary to accurately monitor the conditions inside the cabin in real time, and it is assumed that multiple sensors for temperature, humidity, illumination, and other parameters will be installed. If the operating power for each sensor is supplied by wire, many cables are installed to connect the power source and each sensor, which increases the cost and weight of the cables and makes it difficult to easily change the sensor positions or add new sensors. On the other hand, in the case of a wireless power transfer sensor, cables connecting each sensor are not necessary, thus reducing cable cost and weight. In addition, the sensors can be easily repositioned or installed later, which is desirable from the standpoint of expandability.

Wireless power transmission methods include electromagnetic induction, electric coupling, and radiative transmission using microwaves.(1) Although the electromagnetic induction and electric coupling methods have high transmission efficiency, the transmission distance is short, and a power transmission source is required for each sensor in the vehicle cabin. In this study, we investigated a radiative transmission method using microwaves, which has a longer transmission distance by using radio waves and can supply power to multiple sensors with a single transmission source (Fig. 1).

2. Configuration of the Wireless Power Transfer System

Three transmission frequency bands of 920 MHz, 2.4 GHz, and 5.7 GHz are allowed for radiative wireless power transfer systems.(2) Figure 2 shows the configuration of the system to the wireless power transfer sensor investigated in this study. In this study, the transmission frequency was selected to be 920 MHz, which is also used in radio frequency identification (RFID)*1 systems. Transmission power and antenna gain were set to 1 W and 6 dBi, respectively, which are the upper permissible limits for a radiative wireless power transfer system. Assuming the interior of a passenger car, the maximum transmitting and receiving distance is approximately 2 m. In this case, the power that can be received by the receiving antenna is on the order of 100 µW. In order to convert such weak high-frequency power into DC power, a high-efficiency rectenna*2 consisting of a receiving antenna and a rectifier circuit is required.

A rectenna consists of the antenna and rectifier circuits which are generally designed separately, and the impedance of the antenna and rectifier circuit is set to 50 Ω.(3) While the antenna and rectifier circuits can be optimally designed and evaluated separately, a matching circuit to 50 Ω is required between the antenna and rectifier circuit, which reduces conversion efficiency due to losses in the matching circuit.

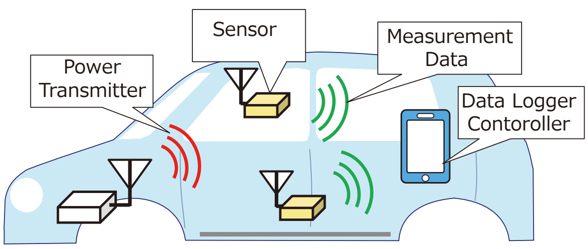

Fig. 1. Powering multiple sensors via radio wave transmission

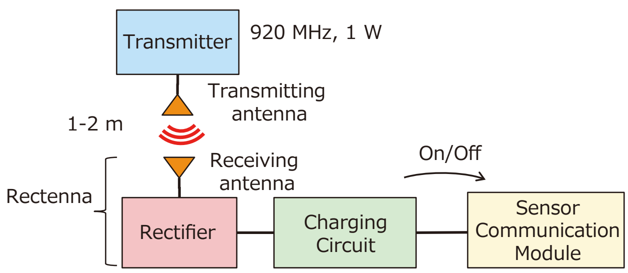

Fig. 2. Wireless power transfer system

In contrast, a rectenna with a configuration that does not require a matching circuit has been studied by connecting a rectifier directly to the output end of the small loop antenna (SLA) and resonating it as a whole.[(4)] A rectenna with an impedance transformed small loop antenna (IT-SLA) has also been studied to reduce the size of the antenna.[(5)] Since the space available for rectenna installation in the vehicle cabin is limited, the wireless power transfer system studied here adopts a rectenna with IT-SLA, which allows the rectenna to be configured with more compact dimensions.

In addition, while the rectenna receiving power is about 100 µW, the power consumption of the sensor and the communication module (2.4 GHz short-range wireless communication) that transmits sensor measurement data is several mW, so the sensor and communication device cannot operate continuously. In this study, a charge circuit was configured to suspend the sensor and communication module until it is charged to a power level that allows the sensor and communication device to operate.

2-1 Rectenna

Figure 3 shows the configuration of the rectenna with SLA designed using the method in Reference 4. The rectifying circuit is a full-wave rectifier, and the rectifier diode is Skyworks SMS7630. Since the rectenna conversion efficiency (rectenna output power/input power) is maximized when the impedance of the antenna is Zr = 4 kΩ and the load resistance Rr = 7 kΩ, we designed SLA with an impedance of 4 kΩ. The dimensions of the SLA designed in this study are Φ74 mm (0.23λ), which is smaller than a typical dipole antenna (0.5λ) with a 50 Ω design, but to improve the freedom of installation inside the vehicle cabin, it is desirable to make the antenna even smaller.

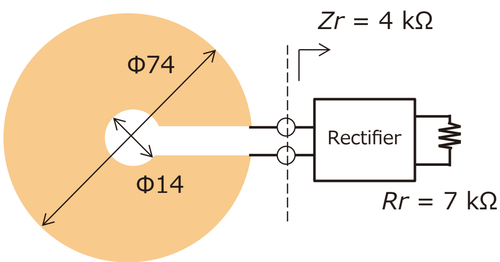

Fig. 3. Rectenna with SLA

Therefore, we designed a rectenna with IT-SLA by the method described in Reference 5. The impedance of the antenna becomes higher when the loop outer diameter is smaller and the loop width is narrower. Therefore, in the case of an antenna smaller than the SLA designed in Fig. 3, the antenna impedance is higher than the SLA designed in Fig. 3 and cannot be matched with the rectifier circuit. Therefore, a rectenna with IT-SLA is composed of a capacitor Cs connected between the antenna and the rectifier circuit, as shown in Fig. 4. The equivalent circuit is shown in Fig. 5. The SLA is represented by a series connection of a voltage Va induced in the SLA, a resistance Ra, and an inductor La. The voltage Vc generated in the SLA is divided by the capacitor Cs, and the voltage Vr applied to the rectifier is $1/n$ times Vc ($n = 1/(1+2Cr/Cs)$). This effect is equivalent to inserting an impedance transformer with a transformation ratio of n^2:1 between the antenna and the rectifier circuit. By using this configuration, the impedance of the antenna can be made n^2 times higher than in the case of the design in Fig. 3, which allows the antenna to be made even smaller. The higher the antenna impedance, the smaller the antenna can be, but the less power the antenna can receive. In this study, we designed and fabricated a rectenna with an impedance transformation ratio of 9:1 (n = 3) to strike a balance between antenna miniaturization and reduction in received power.

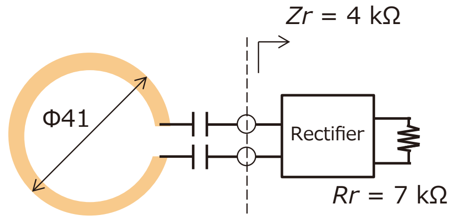

Fig. 4. Rectenna with IT-SLA

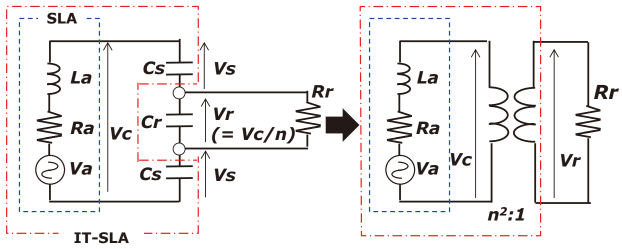

Fig. 5. Equivalent circuit of rectenna with IT-SLA

The outer diameter of the designed IT-SLA is Φ41 mm (0.13λ). Compared to the rectenna designed in Fig. 3, it achieves a smaller size of approximately 0.55 times the outer diameter (approximately 0.3 times the area) than IT-SLA.

The exterior of the rectenna prototype is shown in Photo 1. A small loop antenna was created on the surface of a printed circuit board (Megtron 7, t = 0.2 mm), and a rectifier circuit was mounted on the back. A rectenna prototype was placed at 1 m from the power transmitter, and the rectenna output voltage was measured when the load resis-

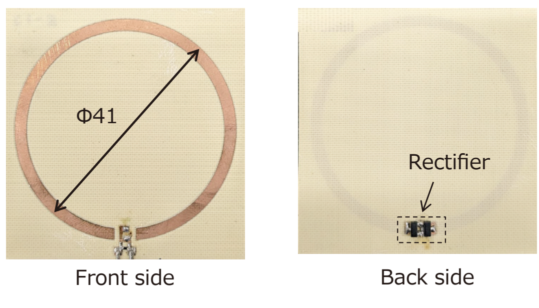

Photo 1. Exterior of rectenna phototype

tance Rr = 7 kΩ was connected to the rectenna (Fig. 6). The output voltage reached its maximum at 920 MHz, and stable characteristics were obtained over a wide frequency band of 20 MHz or more, where the minimum voltage of 0.5 V or more, which is required to drive the charge circuit in the subsequent stage, can be obtained. The rectenna conversion efficiency was confirmed to be over 80% at 920 MHz (Fig. 7).

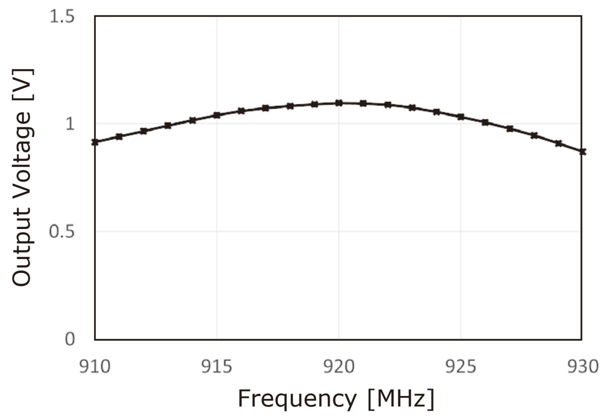

Fig. 6. Rectenna output voltage

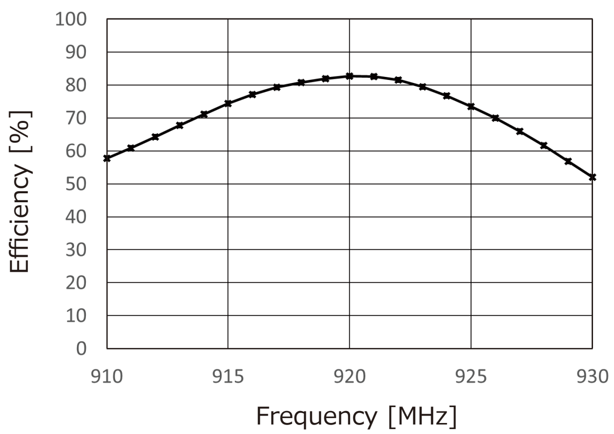

Fig. 7. Rectenna efficiency

2-2 Charge circuit

While the rectenna receiving power is as small as 100 uW, the power consumption of the sensor and the communication module that transmits sensor measurement data is as large as several mW, and the sensor and communication device cannot operate continuously. Therefore, it is necessary to install a charge circuit between the rectenna and the sensors/communication module that suspends the sensors and communication module until they are charged with enough power to operate, and operates the sensors and communication devices when the charging is complete (Fig. 2).

The schematic configuration and operation of the charge circuit designed for this study are shown in Figs. 8 and 9. The power input to the charge circuit charges the battery (BAT) up to a predetermined power level at which the sensors and communication module can operate. When the battery voltage rises to a voltage equivalent to the predetermined power, the voltage comparator activates the timer IC to operate the sensors and communication module at set time intervals. When the battery terminal voltage drops below the predetermined voltage, the timer IC stops and the battery is recharged to a power level that allows the sensors and communication module to operate.

A power supply was connected to the charge circuit prototype, and its operation was verified. When the battery terminal voltage rose to a predetermined voltage, the sensor and communication module operated, and the receiving terminal confirmed that the sensor measurement data was transmitted from the communication module.

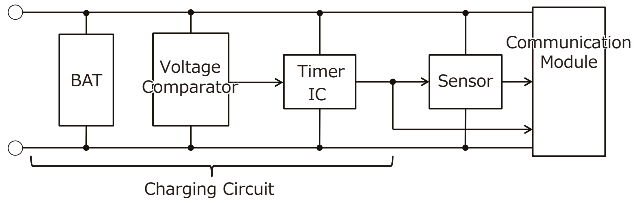

Fig. 8. Charging circuit

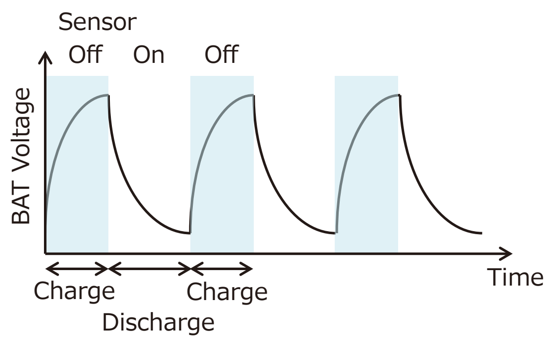

Fig. 9. Operation of the charge circuit

3. Car Installation Study of Wireless Power Transfer System

In this study, we assumed the temperature control system in a passenger car cabin as the use case of the wireless power transfer system. By using a temperature control system to measure the temperature at each seat in real time and optimize the air conditioner temperature control, it is expected to improve comfort at each seat and reduce air conditioner power consumption, thereby improving fuel and electric power efficiency.

3-1 Installation point of wireless power transfer sensor

We studied the position of the temperature measurement for each seat in the temperature control system. Since the head is susceptible to temperature discomfort, we assumed the temperature measurement positions to be near the head of each seat and used the method of controlling the air conditioning temperature based on these measurements. In order to measure the temperature near the head, a wireless power transfer temperature sensor was built into the headrest.

A wireless power transfer temperature sensor combining the rectenna, charge circuit, temperature sensor, and communication module, for which elemental prototyping was conducted in Chapter 2, was built into the headrest (Photo 2), and its operation was verified. As a condition for operation checks, we assumed a case in which the power transmitter was installed in the center of the roof of a passenger car. In this case, the distance between the power transmitter and the headrest is approximately 0.5 m. In the experimental system shown in Photo 3, which simulates this case, we actually supplied power wirelessly (920 MHz, 1 W) to the wireless temperature sensor and confirmed that the communication module transmitted temperature measurement data at intervals of about 30 seconds.

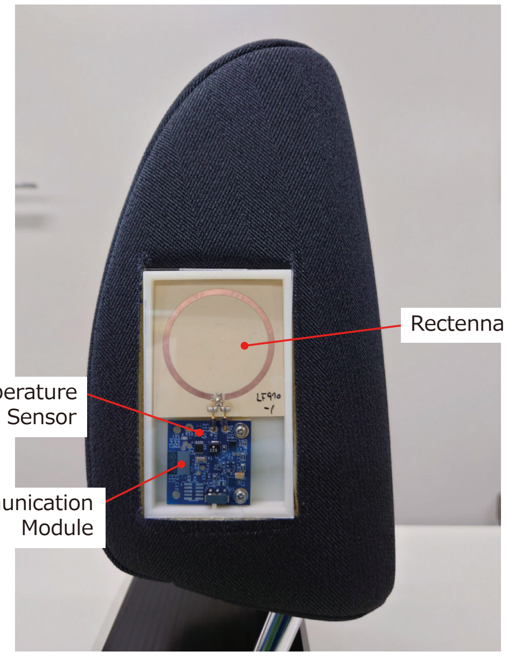

Photo 2. Wireless power transfer sensor in headrest

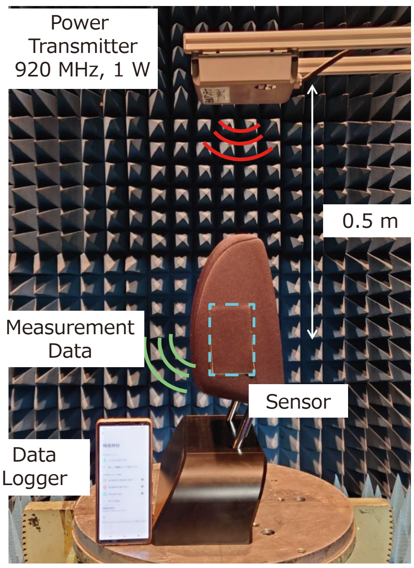

Photo 3. Wireless power transfer experiment

3-2 Installation position of the transmitting antenna

To determine the optimal position for installing the transmitting antenna, the distribution of electric field strength inside the passenger car cabin was calculated using electromagnetic field simulation. We aimed to locate the transmitting antenna in a way that ensures high electric field strength near the headrest, while minimizing regions of low electric field strength within the cabin. As a result, it was found that positioning the transmitting antenna at approximately the center of the roof is most suitable. The distribution of the electric field strength inside the cabin is illustrated in Fig. 10. In the wireless power transfer experiment described in section 3-1, the electric field strength surrounding the wireless sensor was measured at 8 V/m. In this representation of the electrical field strength distribution, values of 8 V/m or higher are obtained in the majority of the cabin area, confirming through simulation that the wireless sensor tested in the previous section can function properly within the cabin.

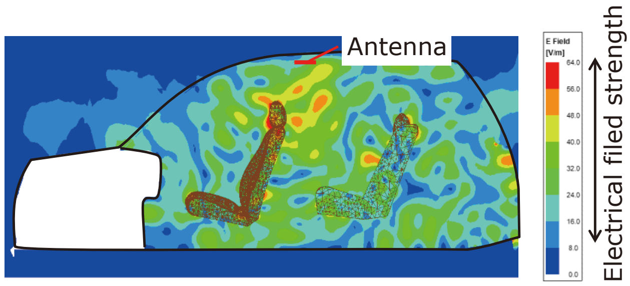

Fig. 10. Electric field strength within the cabin

4. Conclusion

We conducted an investigation into the feasibility of radiative wireless power transfer for sensors expected to be installed inside vehicle cabins. We confirmed that a temperature sensor integrated into the headrest can operate at 30-second intervals using wireless power transfer at a frequency of 920 MHz and a power of 1 W. Additionally, through simulation of the electric field strength distribution inside the cabin, we verified that the sensor can operate within a large portion of the cabin area. We further confirmed that the electric field strength distribution in the cabin provides sufficient power for the sensor to function in most of areas.

As part of future efforts toward implementation in actual vehicles, we will focus on developing rectennas in close proximity to metal objects such as doors. We will also explore methods to improve rectenna installability through the use of flexible printed circuit boards and further miniaturization. Furthermore, we plan to conduct tests to verify the operation of the wireless power transfer sensor under conditions suitable for installation in actual vehicles.

• Megtron is a trademark or registered trademark of Panasonic Holdings Corporation.

Technical Terms

*1 Radio frequency identification (RFID): A system that utilizes radio waves to read and write data from IC tags without contact. It is widely used in inventory control and self-registration systems.

*2 Rectenna: A device that combines a rectifier and an antenna, converting radio waves received by the antenna into direct current using the rectifier. It is short for "Rectifying Antenna."

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