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Development of an RF Power Supply for Wireless Charging Systems and Efforts for Its Implementation in the Society

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ABSTRACT This paper reports on the development of the Radio Frequency (RF) power supply technology and results of demonstration experiments aimed at the implementation in the society of an electric field coupling-type wireless charging system developed for the micro-mobility. When using existing MHz-band RF power supplies for the Wireless Power Transfer (WPT), large size and low conversion efficiency are issues. In particular, when applying to the low power consumption of about a few hundred watts, a small and highly efficient RF power supply is required. Therefore, as a solution, we developed a class E inverter technology using GaN devices and achieved a high conversion efficiency. Also, we summarized the direction of its institutionalization for the implementation in the society and conducted demonstration experiments to show the usefulness of an electric micro-mobility and the wireless charging. We are reporting these activities.

1. INTRODUCTION

The WPT technology is attracting the attention as a next-generation technology that is expected to dramatically improve the convenient access to the power supply. This technology is being increasingly applied in fields such as wireless charging of Electric Vehicles (EVs), smartphones, medical equipment, etc.

In particular, since the electrification of passenger cars is accelerating against the backdrop of energy issues, an expectation for the WPT to EVs is also growing. On the other hand, Japan was the world leader to institutionalize the WPT to EVs in the 2010s, but at that time, the spread of EVs themselves was delayed, and the commercialization did not progress. As of 2024, a new organization to promote the spread of EVs and the social infrastructure of EV wireless power supply, the Wireless EV Alliance (an organization established as a place for private companies and research institutions to cooperate and as a window connecting government agencies and industry in order to develop the EV wireless power supply as a social infrastructure), has been launched, and activities for the product development and the commercialization are becoming more active.

In addition, in recent years, not only EVs but also various forms of electrified mobilities and robots have been increasing. In 2023, the revised Road Traffic Act was enacted, and new vehicle classifications were created for sidewalks and public roads, including "small vehicles for transportation", "remotely controlled small vehicles", and "specific small motorized bicycles", of which electric kick scooter is a typical example. Against this backdrop, this paper reports on the electric field coupling- type wireless charging system developed with a focus on the micro-mobility, which is used on sidewalks, facilities, and public roads at a lower speed than EVs, and on the efforts of demonstration experiments for its implementation in the society.

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2. REGARDING THE STATUS OF THE WPT INSTITUTIONALIZATION

2.1 Status of International WPT Institutionalization

The institutionalization of the WPT is being promoted through the development of international regulations and guidelines from the perspective of electromagnetic frequency usage and safety. The International Telecommunication Union (ITU) and the International Electrotechnical Commission (IEC) are leading the formulation of regulations, and in particular, with regard to the use of frequency bands, a deep care must be taken to ensure that the WPT does not interfere with other wireless communications. Table 1 summarizes regulations, safety standards, and Electromagnetic Compatibility (EMC) regulations by region.

Table 1 WPT regulations by region.

Item	USA	Europe	Japan
Regulation bodies	FCC	CE marking RED, EMC directive	MIC METI
Safety standard	IEEE C95.1, UL	ICNIRP IEV 62368-1	Radio wave protection guidelines PSE
EMC regulation	FCC Part15/18	EN 55011 EN 301 489 series	Radio law VCCI standard in some cases

In the United States, regulations on the WPT equipment are mainly managed by the Federal Communications Commission (FCC). FCC regulations set standards for the operation of wireless equipment, and the WPT technology requires the certification based on FCC Part 15 (unintentional radiators) and Part 18 (industrial, scientific, and medical equipment). This mandates that the equipment prevents an interference with wireless communications and other electronic equipment. Regarding the safety, IEEE C95.1 standard specifies electromagnetic exposure limits for the human body, and the equipment must comply with this standard. In addition, Underwriters Laboratories (UL) provides appropriate safety standards by conducting safety tests to ensure that the WPT equipment avoids risks such as fire, electric shock, etc. Regarding EMC regulations, the equipment must comply with FCC regulations and are designed not to interfere with surrounding wireless communication equipment. This equipment generally uses low-frequency bands (tens of kHz to several MHz), and the radiation from the equipment must be appropriately controlled.

In Europe, regulations on the WPT equipment are mainly managed through CE marking. CE marking indicates that a product complies with all standards of the European Economic Area (EEA), and the WPT equipment is required to comply with the Radio Equipment Directive (RED) and EMC Directive. This ensures the wireless communication performance and the electromagnetic compatibility of the equipment. In addition, regarding the safety, the Low Voltage Directive (LVD) and other directives are applied. Safety regulations stipulate limits of the electromagnetic exposure to the human body based on the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the equipment is designed based on this. In addition, the IEC 62368-1 standard is applied, and standards are set for the structural safety of the WPT equipment and for managing the risks caused by temperature rise. Regarding EMC regulations, EN 55011 (emission standard for industrial and medical equipment) and EN 301 489 series (EMC standard for wireless equipment) are applied. These standards aim to minimize the interference with surrounding wireless and communication equipment, and play an important role in the design of the WPT equipment.

In Japan, the WPT equipment is mainly regulated by the Ministry of Internal Affairs and Communications (MIC) and the Ministry of Economy, Trade and Industry (METI). Under the Radio Law, the WPT equipment is classified as the “RF use equipment”. Unwanted radiation emitted by RF use equipment can cause an interference and a noise, and may interfere with other wireless communications, so the “installation permission” is required. As an exception, the equipment of 50 W or less does not require an application for installation permission. In addition, when modulating the transmission power in-band to communicate the information, it is treated as the “specific wireless equipment” and may be required to obtain the Technical Standards Conformity Certificate (TSCC), so a care must be taken when installing it. Regarding the safety, radio wave protection guidelines have been established, and the electromagnetic wave exposure of the WPT equipment is managed based on these guidelines. In addition, the safety testing of electrical equipment based on the Electrical Appliance and Material Safety Act (PSE) is also required, and standards to avoid risks such as fire, electric shock, etc. are applied. Regarding EMC regulations, it is required to suppress the generation of unwanted radio waves mainly in accordance with the Radio Law and the standards of the Radio Law and Voluntary Control Council for Interference (VCCI).

2.2 Status of the WPT Institutionalization in Japan[1)]

2.2.1 Legal status of the proximity type WPT equipment

In Japan, under the Article 100 of the Radio Law, the equipment uses the RF current with 10 kHz or higher frequency is considered to be an RF use equipment, and since such equipment generate an unnecessary radiation and a conduction noise, and may interfere with broadcasting and wireless communications, it is stipulated that the permission must be obtained from the MIC when installing such equipment. The WPT equipment is no exception, and the equipment that uses radio waves of 50 W or more are treated as the “RF use equipment” under Article 45 of the Enforcement Regulations of the Radio Law, and an individual installation permission is required for each equipment. The WPT equipment that is type-designated or have a transmission power of 50 W or less does not require the installation permission.

Japan is the world’s leading country in the institutionalization of the WPT. On March 15, 2016, the MIC Ordinance No. 15 was promulgated and put into effect, and Articles 45 and 46 of the Enforcement Regulations of the Radio Law were amended, and the type-designated WPT equipment was added as shown in Figure 1. The type designated WPT equipment is expected to be widely sold, used, and disseminated because an individual installation application is no longer required and the procedure is simplified. However, in order to receive this type designation, it is necessary to comply with standards such as measurement methods for interference voltage and unwanted emissions, and safety facilities for radio wave strength, based on Notifications No. 69 to 71 of the MIC of 2016.

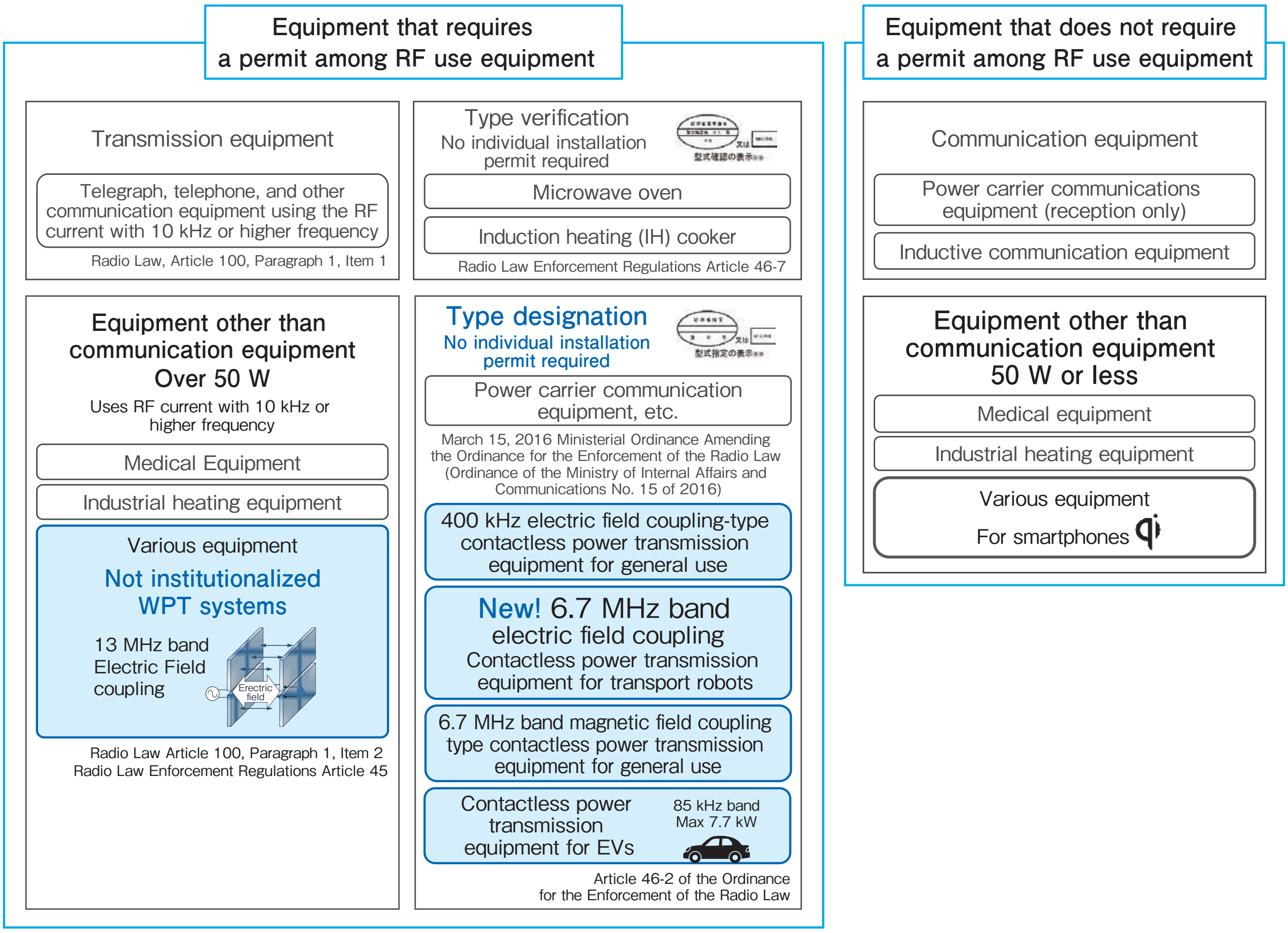


Figure 1 Legal status of the proximity type WPT equipment.

Recently, a new method of the "contactless power transmission equipment for transport robots", which uses an electric field coupling method in the 6.7 MHz band, has been added. This will enable Automated Guided Vehicles (AGVs) and robots used in factories and logistics centers to be charged and powered without cables. In particular, the fact that the power supply can continue even during the operation has attracted the attention as a solution to the declining working population and issues in the logistics industry. It is thought that in the future, the institutionalization of the rapid charging and the high-power support for industrial equipment will also progress.

2.2.2 Legal status of the space-transmission type WPT

Space-transmission type WPT equipment that transmits a power of about 1 W for IoT equipment and sensors is treated as the "specific wireless equipment". The amendment to the ministerial ordinance was implemented by the MIC Ordinance No. 38 "Ministry Ordinance Partially Amending the Radio Law Enforcement Regulations, etc." on May 26, 2022, and the 920 MHz, 2.7 GHz, and 5.4 GHz frequency bands are allocated to the spatial transmission type WPT, enabling it to be established as a premises radio station for a wireless power transmission. In particular, the 920 MHz band has already been legally established as a specific wireless equipment, and if a product is marked with a technical suitability mark, which indicates that it complies with this technical standard under the Radio Law, the radio station license procedure can be omitted and greatly simplified. Furthermore, as of 2024, further amendments to the ministerial ordinance are still being considered, and the addition of frequencies in the 2.4 GHz and 5.7 GHz bands is also being considered.

3. DEVELOPMENT OF THE ELECTRIC FIELD COUPLING TYPE WIRELESS CHARGING SYSTEM

3.1 Regarding the Wireless Charging Systems

The basic configuration of the wireless charging system is shown in Figure 2. It consists of a RF power supply that generates a high frequency AC power, a coupler that transmits a power wirelessly, and a receiving circuit that controls rectification and charging. We are developing total solutions that charge batteries from a commercial power supply. This section will focus on the electric field coupling type coupler that transmits a power using an electric field, which is the feature of our technologies, and the RF inverter that converts the DC in the RF power supply into the high frequency.

3.2 Features of the Electric Field Coupling Type Coupler

As shown in Figure 3, a meander line a) and a flat electrode b) coupler structures are being considered for the electric field coupling type WPT. For the meander line

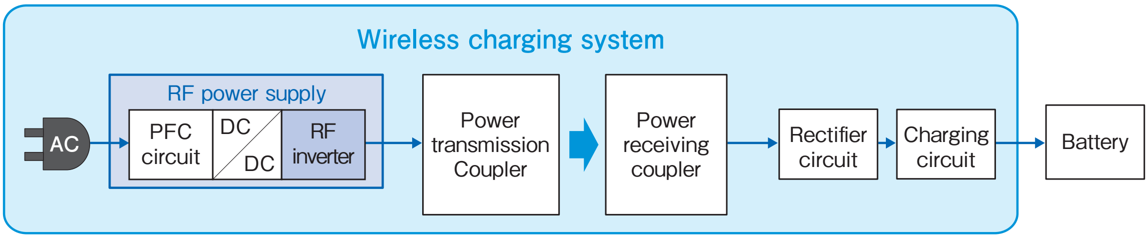


Figure 2 Wireless charging system configuration.

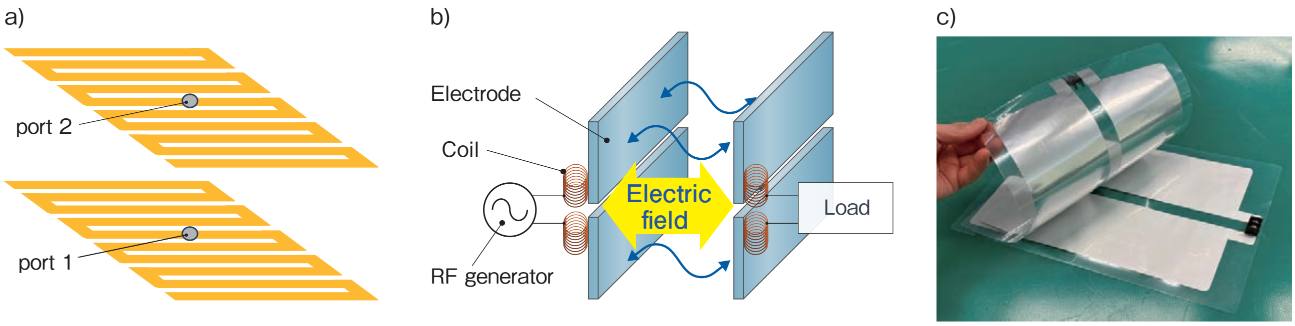


Figure 3 Schematic diagram of the electric field coupling type coupler.
a) Meander line shape. b) Parallel plate shape. c) Composed of aluminum foil.

shape, a planar structure can be used since the resonance caused by the inductance and the capacitance of the pattern itself are utilized and no additional inductance is required. However, due to the length of the transmission line and the pattern structure, skin and proximity effects increase the loss at high frequency bands when the RF current flows.

On the other hand, when using flat electrodes, an additional inductance such as a resonance coil, etc. is required, but a meander line pattern is not required and the loss at high frequency bands can be reduced. By actively using the resonance phenomenon, a high voltage is generated between the electrodes, and the current flowing into the electrodes themselves can be reduced. This allows the electrodes to be made of inexpensive metal materials such as aluminum, iron, etc., which have a lower electrical conductivity than copper. The coupler has a simple configuration consisting of a flat electrode and a resonant coil connected together, and the use of electrodes made of metal foil or other materials allows for a lightweight and flexible structure.

3.3 Development of the RF Inverter

3.3.1 Overview of the inverter technology

The inverter technology refers to devices and circuits that convert Direct Current (DC) power into Alternating Current (AC). The basic operating principle is to reverse the voltage extracted from the DC power supply at a certain period to generate the AC waveform. This allows the energy obtained from the DC to be converted into the AC power of different frequencies and voltages. The WPT equipment using the MHz band often uses frequencies such as 6.78 MHz, 13.56 MHz, and 27.12 MHz in the license-free Industrial Scientific and Medical (ISM) bands, which are allocated for the general use in medical, industrial, and scientific fields. The equipment that supplies these RF powers is called the RF power supply, and the inverter built into this is called the “RF inverter”.

3.3.2 Regarding the class E inverter

Advances in power semiconductors and circuit topologies have led to higher frequencies in power supply equipment, and this contributes to improve the conversion efficiency and the miniaturization. Higher frequencies reduce the number of turns in coils and transformers, reducing losses and simplifying the cooling design. This has made it an important technology for mobile phone chargers and in-vehicle equipment, which require small sizes and lightweights.

Switching power amplifier is an equipment that efficiently amplify signals and power, and is used in the fields of audio, communication, medicine, and automobile. In order to minimize switching losses, the Zero Voltage Switching (ZVS) and the Zero Current Switching (ZCS) are used, and a compact and space-saving design that eliminates the need for heat sinks and fans is realized. The class E amplifier is a typical circuit of switching power amplifier. The class E amplifier was introduced by Sokal in 1975, and applications are expected since the inverter with a high frequency and a high efficiency is realized using a simple circuit configuration which has only one switching element. Figure 4 shows the circuit diagram of a conventional class E inverter and its operating principle. It is possible to design the circuit constant by theoretically solving the equation under the condition that three of the four points where the Field Effect Transistor (FET) voltage and current waveform switches on and off are zero. In the ideal operating condition, either the FET voltage or current can always be zero, so no power is consumed due to the switching loss, and the efficiency can be increased even when switching at high frequencies.

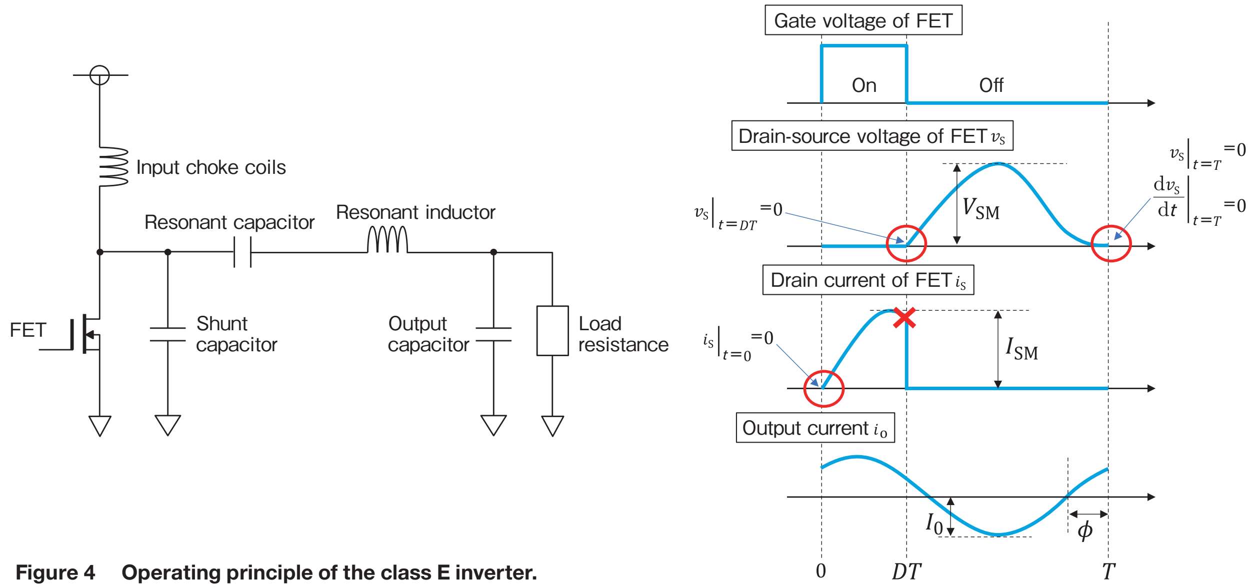


Figure 4 Operating principle of the class E inverter.

3.3.3 Regarding the charging power for electric applications

In developing a wireless charging system, the general charging power for electrified mobility, drones, and robots is summarized in Table 2. While a large power is required for the industrial use, it can be seen that for the home use, just under 1000 W is required. In this report, we aimed to achieve a high efficiency in areas where relatively small charging power is required.

3.3.4 Design of the class E inverter

This paper reports on the development example of the Class E inverter optimized for 50 W and 200 W. Target specifications are shown in Table 3. Voltage and current waveform were defined so that the ZVS and the ZCS were established, and element values were designed by solving equations. Figure 5 and Table 4 show the main circuit diagram of the developed class E inverter, design values of the elements obtained by the calculation, and

Table 2 List of common charging powers for electric applications.

Classification	Equipment example	Typical charging power (W)	Remarks
Home appliance robot	Cleaning robot (e.g. Roomba) Lawnmower robot	20-150 W	Many energy-saving designs for home use
Small drone	Hobby drones (e.g. DJI Mini-series)	50-300 W	Lightweight and uses a small capacity battery
Mobility	Electric scooter, Electric wheelchair	200-1000 W	The larger the battery, the higher the charging power required
Industrial drone	Agricultural drones, Inspection drones (e.g. DJI Matrice)	500-2000 W	Equipped with a large-capacity battery for long-distance operation and heavy load transportation
Industrial robot	Welding robot, Assembly robot	1000-5000 W	High-load work is carried out in the factory, so very high charging power is required

Table 3 Target specifications for class E inverters.

Item	50 W version	200 W version
Inverter output	50 W	200 W
Frequency	13.56 MHz	
Output impedance	50 Ω	
Drain efficiency	＞90%	

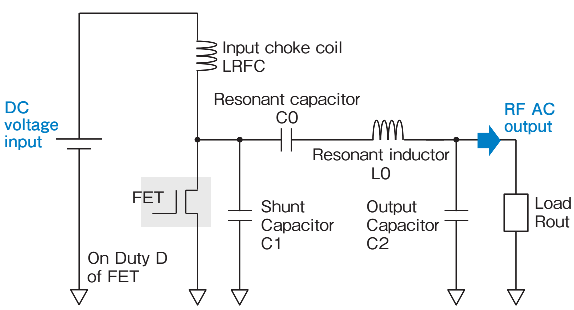


Figure 5 Circuit diagram of the class E inverter.

Table 4 Circuit parameters.

Parameter	Symbol	Design value	Assembly	Unit
Load	Rout	50	50	Ω
Output capacitor	C2	540	540	pF
Shunt capacitor	C1	373	302	pF
Resonant capacitor	C0	810	810	pF
Resonant inductor	L0	561	564	nH
Input choke coil inductor	LRFC	10	10	µH

element values of implemented parts. GaN-FETs were used in this development, and a highly efficient operation at 50 W and 200 W was achieved by changing the FET.

3.3.5 Actual equipment evaluation of the class E inverter

The waveform and efficiency of the developed class E inverter were measured. The developed class E inverter and the measurement system are shown in Figures 6 and 7.

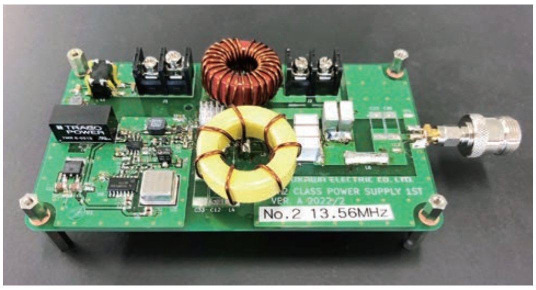


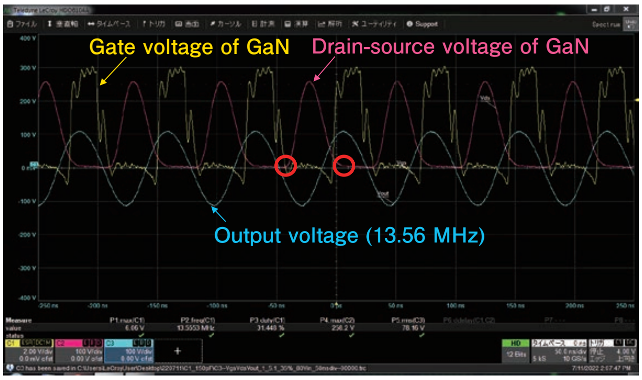
Figure 6 Developed class E inverter (size: 145 x 80 x 25 mm).

Measuring equipment	Manufacturer	Model number
Input power	KIKUSUI	PWR400H
Input power meter	HIOKI	PW3335
Oscilloscope	Lecroy	HDO6104A-MS
Output RF power meter	Bird	MODEL4421
Load	TMT	T50013AN 50 Ω

Figure 7 Measurement system.

Figure 8 shows the waveform measurement results. The GaN drain-source voltage waveform had a zero-voltage value and a zero slope when the switch was turned on and off, and the expected waveform was observed. Also, the output voltage waveform was sinusoidal, and it is believed that the class E operation was achieved.

Figure 9 shows results of a Fourier transform of the output power waveform and analyzing the signal spectrum. As a result, it was found to contain the spurious harmonic of the second to the fourth harmonic wave. In the actual circuit, since there is a difference between the turn-on and turn-off time of the FET, it is thought that an even-order spurious component is observed because the duty ratio of the signal source is adjusted instead of 50%. In addition, odd-order components are also seen because the original signal source is a square wave. Past studies



* GaN gate voltage shows distortion in waveform due to long GND probing.
* Measured waveforms have a phase shift because the deskew is not performed.

Figure 8 Output waveform of the class E inverter at 50 W output.

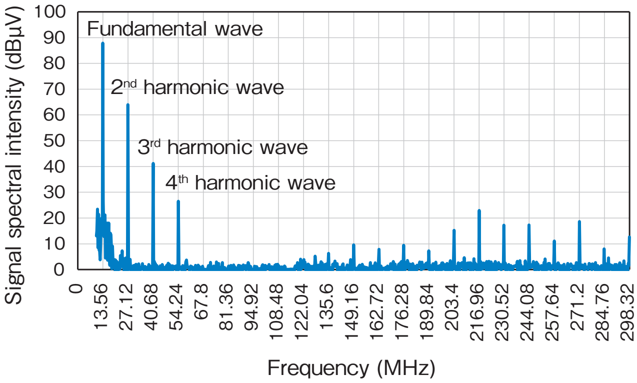


Figure 9 Power spectrum of the output waveform of the class E inverter at 50 W output.

have shown that these spurious components can be prevented by installing a low-pass filter at the output. It is therefore necessary to design and manufacture a low-pass filter for this inverter so that harmonic components are suppressed from output.

Figure 10 shows the output power and the drain efficiency. After selecting the GaN-FET to be installed, 50 W and 200 W versions were evaluated. In the 50 W version, the maximum output at which the thermal design is valid with natural cooling is 50 W, and a drain efficiency of 91% was achieved at that time. In the 200 W version, the maximum output is 200 W, and a drain efficiency of 95%

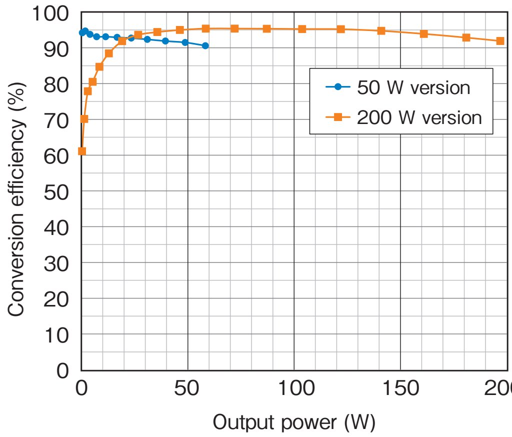


Figure 10 Drain efficiency of the class E inverter.

was achieved at an output of around 100 W. Table 5 and Figure 11 show these results and precedent examples. From this, it can be seen that a highly efficient inverter has been designed in the low output power range. In the future, we will continue to improve the output power of the inverter itself and increase the output using power combining technology, etc., in order to apply it to applications that require large charging power.

Table 5 Comparison of the 13.56 MHz inverter with previous examples.

Measuring equipment	Circuit topology	Output power	Main circuit conversion efficiency
This study 1 50 W version	Single phase class E	50 W	91.0%
This study 2 200 W version	Single phase class E	200 W	95.0%
Precedent cases (1)[2]	Push-pull class C	400 W	75.5%
Precedent cases (2)[3]	Single phase class E	10 kW	85.0%
Precedent cases (3)[4), 5)]	Single phase Φ 2 class	13 kW	94.6%
Precedent cases (4)[6]	Single-phase Class D Half-bridge	17 kW	87.0%
Precedent cases (5)[7]	Single-phase Class D Half-bridge	28 kW	96.2%

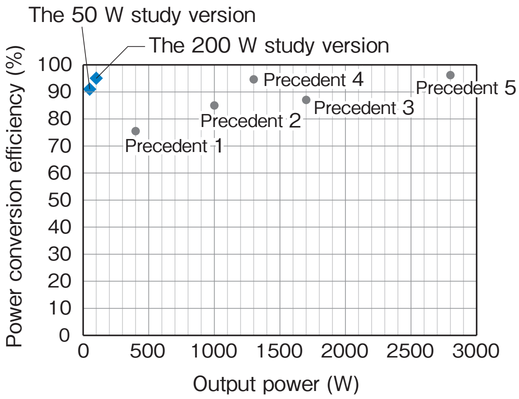


Figure 11 Comparison of the 13.56 MHz inverter with previous studies.

4. DEMONSTRATION EXPERIMENT OF THE WIRELESS CHARGING SYSTEM FOR MICRO-MOBILITIES

4.1 Overview of the Demonstration Test

This paper reports on the results of demonstration experiments aimed at the implementation in the society. Up to this point, we have reported on the development of the RF inverter optimized for the low power. In order to expand wireless charging systems as a social infrastructure, it is necessary to promote the institutionalization so that the application for RF use equipment is no longer required, but there is an aspect that the institutionalization will not progress unless there is a prospect of widespread use of such equipment. Currently, equipment of 50 W or less does not require applications, so the implementation in the society is easy. Therefore, we developed a wireless charging system of 50 W or less for the electric kick scooter as shown in Figure 12 and Table 6, and conducted demonstration experiments to verify the usefulness of wireless charging. The developed system automatically charges the electric kick scooter when it is parked, and the charging can be performed without being aware of the hassle of a wire connection.

Requirements for the battery charging are thought to depend on its use case. When used as a continuous means of transportation, it is necessary to shorten the non-operating time and increase the operating time, so a method of increasing the battery capacity and replacing the battery is appropriate. On the other hand, when used as a means of spot transportation, for example, it can be used as a means of transportation in the morning and evening and only parked during the day. In this demonstration, we conducted experiments focusing on use case where the bicycle is parked for long periods of time, and demonstrated the usefulness of micro-mobility as a means of transportation and the labor-saving effect of the charging operation. We are reporting these results.

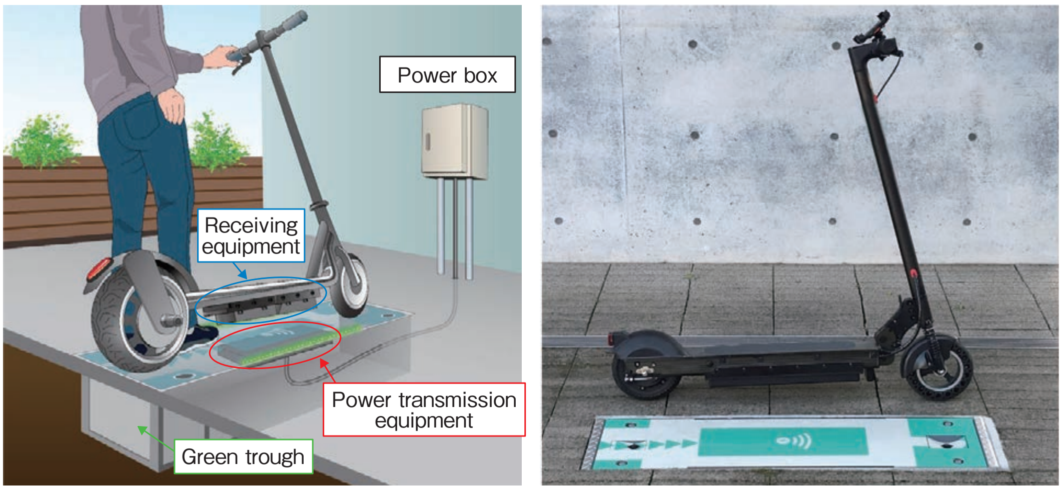


Figure 12 Configuration of the developed wireless charging system.

Table 6 Specifications of the wireless charging system.

Items	Specification
RF power output	50 W
Frequency	27.12 MHz
Transmission distance	Max. 70 mm
Charging power	30 W

4.2 Use Case: Transportation at the Construction Site

A demonstration experiment was conducted at an actual construction site. An electric kick scooter was used as a means of transportation between the office and the construction site, and was parked while working in the office. Charging started automatically when parked. In the experiment, a data logger was installed on the vehicle to monitor the charging voltage and the current, and estimated the remaining battery capacity. Typical daily usage conditions and remaining battery capacity are shown in Figures 13 and 14.

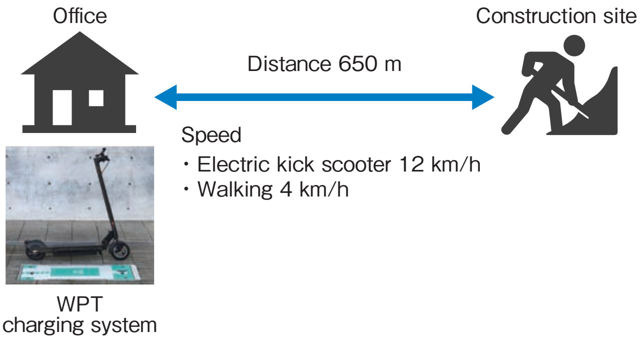


Figure 13 Use case examples in construction sites.

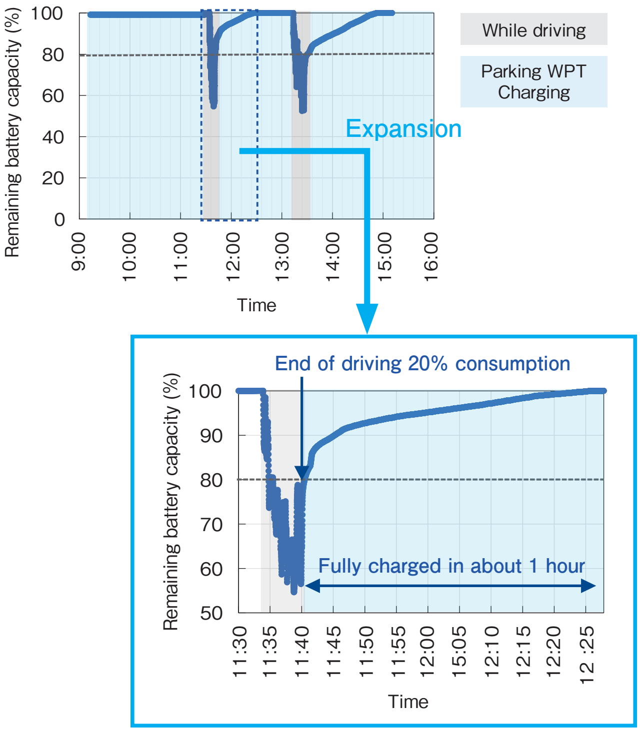
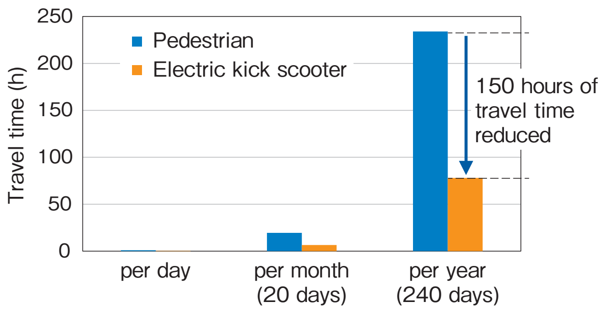


Figure 14 Battery level variation over the course of a day.

Since the office work is main and the use of the electric kick scooter is several times a day to go to the construction site, each ride lasted about 5 to 6 minutes, and the electric kick scooter was parked most of the other time. While the electric kick scooter is running, the remaining battery capacity appears to drop significantly due to the voltage drop caused by the current being generated, but when the electric kick scooter is stopped and parked after running, the consumption is found to be just under 20%. In the use case where the battery is charged while the electric kick scooter is parked for an hour or so, it was found that the remaining battery charge can be maintained at 80-100% without the need for a wired connection and without the need to be aware of the charging.

Figure 15 shows the time saving effect of using micro-mobility as a means of transportation. Assuming three round trips of 650 m each way, it was found that the time saving effect was about 25 minutes per day, and about 150 hours per year (equivalent to about one month's work time). The usefulness of using micro-mobility for relatively short trips of a few hundred meters was also confirmed.



Calculation conditions		Travel time	
One way travel distance	650 m	1 round trip	3 round trips
Pedestrian speed	4 km/h	20 min.	40 min.
Electric kick scooter	12 km/h	7 min.	15 min.

Figure 15 Time-saving benefits of micro-mobility.

5. CONCLUSION

Regarding the electric field coupling-type wireless charging system developed for the micro-mobility, the development of the RF power supply focusing on the low power and demonstration results that were performed actually at the construction site for the implementation in the society were reported. We developed an RF inverter in the RF power supply, achieving a maximum output of 200 W and a drain efficiency of 95% at an output of around 100 W. In addition, the demonstration experiment showed the usefulness of using micro-mobility for short-distance transportation, and by providing an automatic wireless charging technology during parking, the remaining battery capacity can be maintained at 80-100% without the need for a wire connection and without the need to be conscious of charging.

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