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History and Innovation of Wireless Power Transfer via Microwaves

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ABSTRACT Wireless power transfer (WPT) has a long history of over 100 years since the first experiment conducted by Nicola Tesla. However, the most interesting innovation of WPT was born in the 21st century. In this decade, near-field WPT commercialization was advanced, and we now use many near-field WPT products, such as wireless chargers for mobile phones and electric vehicles. In the next decade, we can expect the development of far-field WPT via microwaves, through which we can drive Internet of Things (IoT) sensors without batteries based on transmitted or ambient microwave power. We can charge mobile phones with microwave power. When we focus microwave power on a target by beam forming technology, we can transmit higher wireless power to fly drones or from space to the earth. In conjunction with the research & development of microwave-based WPT, radio regulations suitable for each country need to be discussed. In this paper, I review the history, innovation, and status of the radio regulations of WPT via microwaves with the classification of wide-beam WPT, including harvesting, and narrow-beam WPT.

INDEX TERMS Wireless power transfer, microwave power transfer, far-field WPT, beam forming.

I. INTRODUCTION

A wireless power transfer (WPT) is considered as one of the game-changing technologies. Recently, it is easy to find commercial products of near-field WPT based on inductive coupling technology via a high-frequency magnetic field with coils, such as wireless chargers for mobile phones and electric vehicles. WPT innovation was initiated in the 21st century with the discovery of a resonance coupling WPT by a research group at Massachusetts Institute of Technology [1] in 2006. Before the innovation of resonance coupling WPT, inductive coupling applications of a transformer, an inductive heater, a near-field communication, and a contactless charger were in use for a wireless phone. In addition, a similar technology existed to use the resonance by inductor and capacitance for power factor correction between coils, e.g., in a transformer. When there is no capacitance at coils, reactive power increases and power loss increases. So additional capacitance is put at the coils to decrease reactive power only. In the resonance coupling WPT, resonance phenomena with high Q-factor is applied to increase distance between two coils with keeping high efficiency. So previous inductive coupling with capacitance was not applied as innovative WPT. However, resonance coupling WPT has awakened us to the potential of WPT.

With the expansion of near-field WPT products, extension of WPT distance is desired for convenience so that we can charge batteries automatically. In that respect, a far-field WPT via microwaves can meet expectations. Far-field WPT was first experimented by Nicola Tesla over 100 years ago [2]. Tesla studied both near-field and far-field WPT systems at the end of the 19th century. Unfortunately, no suitable applications of far-field WPT were present at the time, and there was no commercial product of far-field WPT, except radio frequency identification (RFID). Significant progress has been made on far-field WPT after the 1960s [3], [4], and some startup companies were born in the 21st century. In this paper, I review the history, innovation, and status of radio regulations of WPT via microwaves with the classification of wide-beam WPT, including harvesting, and narrow-beam WPT.

II. APPLICATION OF WIRELESS POWER TRANSFER VIA MICROWAVES: 1 – WIDE-BEAM WPT

A. HISTORY OF WIDE-BEAM WPT

WPT research was initiated by Nicola Tesla at the end of the 19th century. He said "This energy will be collected all over the globe preferably in small amounts, ranging from a fraction of one to a few horse-power. One of its chief uses will be the illumination of isolated homes." Tesla built a gigantic coil that was connected to a 200-ft high mast with a 3-ft diameter ball at its top. The device was called the Tesla Tower. Tesla fed 300 kW of power to the coil, which resonated at a frequency of 150 kHz. The radio frequency (RF) at the top sphere reached 100 MV. Unfortunately, the experiment failed because the transmitted power diffused in all directions using 150-kHz radio waves with a wavelength of 21 km. It was a wide-beam WPT similar to a broadcasting system.

After the first WPT trial by Tesla, the history of radio waves has been dominated by wireless communications and remote sensing. In the 1940s, Percy L. Spencer, engineer of Raytheon Company, found microwave (GHz-order radio wave) heating and developed the first microwave oven when he developed a microwave radar for remote sensing. Similar to the development of the microwave oven, the broadcasting system leads to energy harvesting from ambient radio waves. The most well-known application of energy harvesting from ambient radio waves is Germanium radio. No battery is required to use the radio. It receives radio waves both for broadcast and energy. Besides ambient radio waves, energy sources for energy harvesting can be vibration, heat, and electric light, which are ambient weak power around us. The number of scientific papers has increased in the 21st century and recently, some large-scale research projects are ongoing around the world. Recent advances in energy harvesting are led by Internet of Things (IoT) applications. An IoT device generally requires very small power, and the number of IoT devices is expected to increase to trillions. The characteristics of an IoT device is suitable for energy harvesting.

The University of Washington is one of the promoters of RF energy harvesting, and they propose the concept of wireless identification and sensing platform (WISP) [5]. WISP is a family of sensors that are powered and read by UHF RFID readers. WISPs use harvested power from the RF signal generated by the reader. Based on WISP technology, they developed a battery-free phone using RF energy harvesting, and it was operated by combining analog and digital approaches with a power of only 3.48 μW [6].

The drawback of RF energy harvesting is its small power. For example, the measured power density of TV broadcasting waves and mobile phones in Japan is only dozens of μW/m^2 [7]. The advantage of RF energy harvesting is that it obviates the need for a special power transmitter. However, if the user needs more power, it could be used as a far-field WPT system.

RFID was the only far-field WPT product until the 21st century. The conventional RFID system operating at UHF and microwave is defined as ISO/IEC 18000-6 at 860–960 MHz and ISO/IEC 18000-4 at 2.45 GHz. (ISO is International Organization for Standardization, and IEC is International Electrotechnical Commission.) The allowed power is $<$1 W, and the antenna gain is $<$6 dBi. Passive-type RFID uses wireless power and backscatter communication.

Based on RFID technology, wide-beam WPT was developed. Compared with RFID, wide-beam WPT has high versatility. Generally speaking, the wide-beam WPT system is defined as a far-field (Fraunhofer region) WPT system to provide the wireless power to multi users without district target detection. Transmitted RF power is used for the ambient wireless charge of the battery. The RF power and RF information usually rely on independent RF because of radio regulations. However, a recent concept called simultaneous wireless information and power transmission (SWIPT), which is a more useful system, is born [8].

We, Kyoto University, developed the wireless charger for a mobile phone at 2.45 GHz around 2000. It is based on a narrow beam WPT technology developed in Kyoto University from 1980s. We also demonstrated an outdoor wireless charger for a mobile from an airship in 2009 and wireless powered sensors from a drone in 2015. In Kyoto University, RF-powered vital sensors were developed in 2018 with Panasonic Corp. [9]. At first, it was based on a 920-MHz-band RFID system, and the transmitted power was $<$1 W. The developed system can be commercialized even if there is no special radio regulation for WPT. However, more RF power can drive various vital sensors, and we developed a $<$5-W wide-beam WPT system. The field experiment was carried out in 2018 and 2019 at the town hall and a nursing home in the south of Kyoto city in a permitted area for scientific studies. The sensors had batteries; however, they could also be driven without batteries (Fig. 1).

B. KEY TECHNOLOGY OF WIDE-BEAM WPT: RECTENNA

One of the key technologies for both energy harvesting and wide-beam WPT is rectifying antenna or rectenna, which is an RF receiver and converter from RF to direct current (DC) and consists of an antenna and rectifying circuit with a diode or CMOS. We cannot control an RF power density in the energy harvesting system. So increasing RF-DC conversion efficiency of the rectenna is important to increase DC power and output DC voltage.

The RF-DC conversion efficiency has already reached $>$90% at the 2.45 GHz band [10] and $>$80% at 5.8 GHz band [11], respectively, with the Schottky barrier diode (SBD). It is a good efficiency as an energy system. However, the input RF power greater than 1 watt is required to realize the highest efficiency because of the characteristics of the diode. For the energy harvesting and wide-beam WPT, received RF power at a receiver is less than dozens of mW or below mW. The RF-DC conversion efficiency of the rectenna has an input power dependence. The RF-DC conversion efficiency is generally 90% at input power of $>$ 1 W.

How do we increase the RF-DC conversion efficiency of a rectenna with below-mW RF input power? Rectenna is simple, and it consists of an antenna and a rectifying circuit with

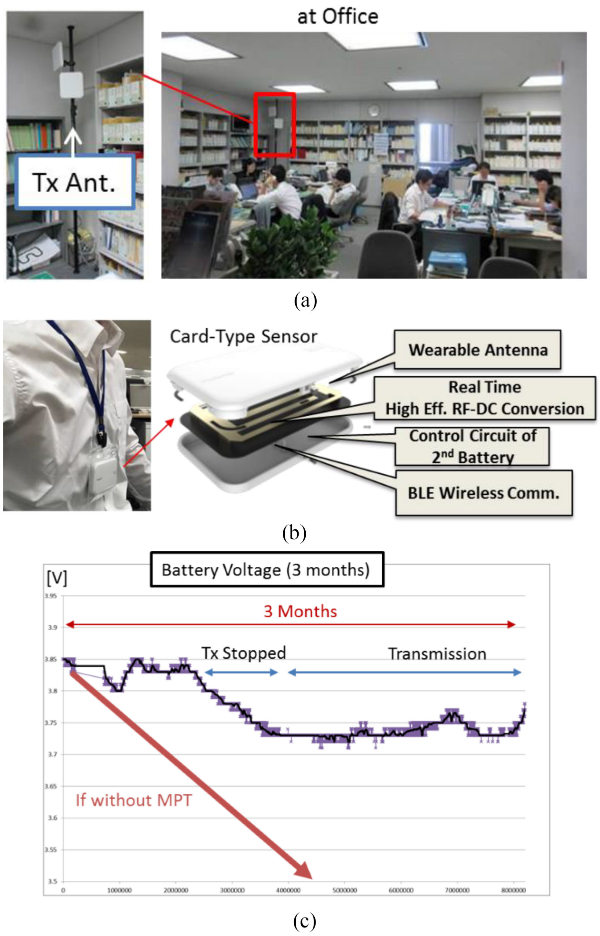


FIGURE 1. Wireless-powered wearable vital sensor system by Panasonic corp. and kyoto university (a) Picture of field WPT experiment in town hall in 2018 (b) Developed wireless-powered wearable vital sensor (c) Measured battery voltage of sensor [9].

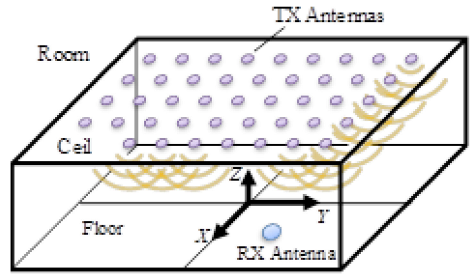


FIGURE 2. Antenna positioning of proposed distributed WPT [15].

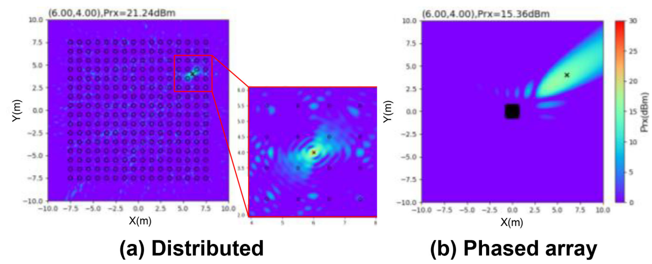


FIGURE 3. Received power distribution on Z = 0 plane [17].

a diode/CMOS. In reference [12], [13], based on the Carnot limit, the theoretical RF-DC conversion efficiency in low-input RF power can be increased by using a diode/CMOS with (1) low series resistance and high junction resistance (e.g., higher Schottky barrier) and (2) higher nonlinearity (e.g., tunnel diode or spin diode). A group at the Eindhoven University of Technology, the Netherlands, developed a rectifier with a tunnel diode in 2019 [14]. For -25 to -10 dBm input 2.4 GHz microwave power, the RF-DC conversion efficiency with the tunnel diode was higher than that obtained using a conventional SBD. Future energy harvesters might exploit the new diodes.

Based on the Carnot limit, a high Q-matching circuit (high-impedance antenna) is also effective to increase the RF-DC conversion efficiency. A group at the University of Liverpool developed wide-band and low-power rectenna with >400-Ω impedance antenna and achieved an RF-DC conversion efficiency of up to 75% from 0.9 to 1.1 GHz and from 1.8 to 2.5 GHz. The optimal input power range was tunable from 0 to 23 dBm by selecting appropriate diodes [15]. Another group at Kanazawa Institute of Technology, Japan, also developed a high-impedance rectenna with a 1.6-kΩ antenna for harvesting digital TV signals at 500 MHz in 2016 [16]. The developed rectennas achieved an RF-DC conversion efficiency of 48.9% at an input RF power of -15 dBm. In addition to the above, the top-level efficiency of 8.7% at an input power of -30 dBm can be achieved.

C. INNOVATION OF WIDE-BEAM WPT

For energy harvesting from ambient RF, the only key technology to obtain higher wireless power is the rectenna because we cannot control RF power distribution. However, when we consider a wide-beam WPT, we have more choices to increase obtained wireless power. We can then control the beam distribution.

Panasonic Corp. in collaboration with a Kyoto University group developed a new distributed WPT system that reduces transmitted power density and improves received power level in 2020 [17]. The proposed distributed WPT system is shown in Fig. 2. The distribution of the received power and the maximum received power on the floor ($Z = 0$) were calculated and measured. Fig. 3 shows the calculated received power distribution when the phases were optimized only at the target position. It can be seen that the proposed distributed WPT system can concentrate power on a very small spot compared with the conventional phased array system. Also, in the phased array system, the received power is steeply decayed as the distance from the antenna increases, but the proposed distributed WPT system can uniformly obtain high power over a wide range.

In parallel, Kyoto University estimates a revised in-room WPT system with a phased array and retrodirective target detecting method, which was proposed by Ossia Corp. [18],

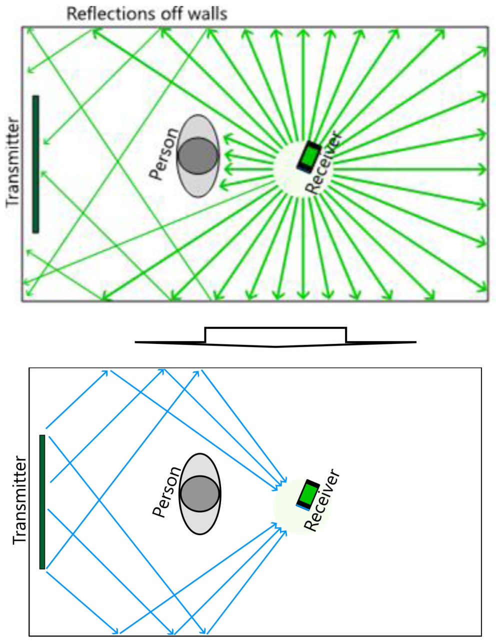


FIGURE 4. Operating principle of the multi-path retrodirective system [17].

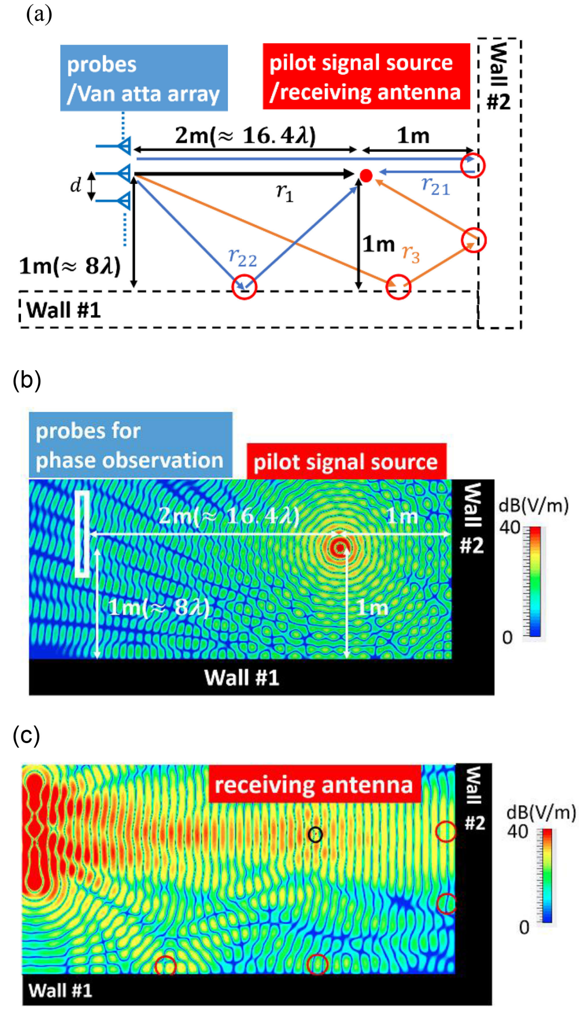


FIGURE 5. Simulation conditions for multi-path retrodirective system with walls #1 and #2 (b) pilot signal of 2.45 GHz from the receiver at h = 1 m (c) microwave power of 2.45 GHz (d = λ/2, 13 elements) [18].

[19]. The Ossia system is based on a multi-path retrodirective method with the phased array by using a phase conjugation of a beacon signal from a target (Fig. 4). At first, a target radiates a beacon signal. At a phased array, power transmitter, the beacon signal is received and phase conjugation is created from the received beacon signal at each antenna in the phased array. As a result of the phase conjugation, power beam is formed to the target even in multi-path circumstance.

The Ossia system was simulated using finite-difference time-domain simulation (Fig. 5) [20], and the phase conjugation in the multi-path retrodirective array of the microwave power beam was compared with only the optimized beam form to maximize the efficiency at the receiver. The multi-path retrodirective method produces the same efficiency and is effective. We also simulated two-target systems in the multi-path circumstance where pilot signals were simultaneously sent from the targets. Using simulation, we reached the same result, indicating that the retrodirective method in the multi-path circumstance is effective even with two targets.

D. REGULATION STATUS OF WIDE-BEAM WPT

In 2016, the International Telecommunication Union Radio communication sector (ITU-R) published the first ITU-R report SM.2392 of WPT via radio waves [21]. It covers all applications of WPT via radio waves, wide-beam WPT to IoT sensors, narrow-beam WPT to fly a target, and Solar Power Satellite. WPT discussions in the ITU-R have a long history since 1978 [22]. After a short break, Question ITU-R210/1 (wireless power transmission) was allocated to ITU-R SG (study group) 1 WP (working party) 1A in 1997. The ITU-R report in 2016 was mainly based on Question R201/1.

In 2019, reports on specified WPT applications such as wide-beam WPT and low-power applications named SM. [WPT. BEAM.IMPACTS] and frequency recommendation named SM [WPT.BEAM.FRQ] were discussed. As a result, "Working Document Towards a Preliminary Draft New Report ITU-R SM. [WPT.WIDE-BEAM.IMPACTS] rev" was accepted by the ITU-R. System specifications for the beam WPT for the first step of commercialization (2020) is shown in the working document (Table 1). In the next meeting of the ITU-R, discussions will be extended based on the working document.

The WPT systems in Table 1 were supported by Japan and the US, where the Federal Communications Commission approved the wide-beam WPT system for different WPT venture companies (e.g., Energous Corp. and Ossia Corp.) in December 2017, June 2019, and October 2019. In the US, WPT approvals are mainly based on industry, science, and medical (ISM) band systems in the 920 MHz and 2.4 GHz bands. Simultaneously with ITU-R discussion, the discussion

TABLE 1. System Specifications for the Beam WPT for the First Step of Commercialization (2020) in "Working Document Towards a Preliminary Draft New Report ITU-R SM." [WPT.WIDE-BEAM.IMPACTS] rev in ITU-R

System		System 1	System 2	System 3
Spec	Frequency	920 MHz bands (915-930 MHz)	2.45 GHz bands (2.40-2.499 GHz)	5.7 GHz bands (5.470-5.770 GHz)
	Output Power	1 W	15 W	32 W
	Antenna Gain	6 dBi	24 dBi	30 dBi
	EIRP	4 W (36 dBm)	65 dBm	70 dBm
	Modulation	TBD	TBD	TBD
	Place of use	Indoor	Indoor	Indoor

toward new domestic radio regulation (RR) for far-field WPT started in Japan in 2019. Discussion is based on a future WPT system scenario in three-frequency bands, 920 MHz, 2.4 GHz, and 5.7 GHz, as shown in Table 2. Parameters for electromagnetic interference evaluation are shown in Table 3. After a tough negotiation with a lot of victims, we have reached an agreement with wide-beam WPT as a new domestic RR in Japan on July 14th, 2020 [23]. The agreed technical condition of the wide-beam WPT is shown in Table 4. It is based on neither the ISM band nor the same wireless application as other wireless communications. It is a great first step for WPT in Japan. We still need further discussion to enact the new RR. We expect that the new RR will be enacted before the end of 2020.

III. APPLICATION OF WIRELESS POWER TRANSFER VIA MICROWAVES 2 – NARROW-BEAM WPT –

A. HISTORY OF NARROW-BEAM WPT

After the failure of the first WPT experiment by Tesla, far-field WPT raised again in the 1960s as narrow-beam WPT using microwave. The narrow-beam WPT system is defined as a radiative near-field (Fresnel region) WPT system to increase beam efficiency, which is theoretically close to 100%, compared to wired power transmission. Generally speaking, the wireless power is focused on one target with strict target detection in the narrow beam WPT.

William C. Brown conducted narrow-beam WPT field experiments in the US [24]. He applied the narrow-beam WPT to a flying drone (small helicopter) via 2.45 GHz microwave from a magnetron in 1964 and 1968. He succeeded in the longest distance narrow-beam WPT in 1975 in Goldstone in the US. In the field experiment, 30-kW DC was received from a 3.4 m × 7.2 m rectenna array, 1 mile from a 26-m diameter parabolic antenna with a 450 kW Klystron at 2.388 GHz. He also achieved 54% DC-DC total system efficiency with 1 kW–2.45 GHz magnetron in a laboratory experiment in 1975. It is still the highest total efficiency for narrow-beam WPT. His technology in the 1960s and 1970s was a microwave tube as a microwave transmitter, similar to the magnetron and Klystron. The injection locking technique of magnetrons and power combining/beam forming are important for narrow-beam WPT and he developed the first injection locking magnetron[25]. Recently it is still developed and revised both in Kyoto University[26] and Sichuan University, China[27].

He also invented a rectenna. The word rectenna was originally proposed by Brown. He developed up to 90% rectenna with GaAs SBD at 2.45 GHz in a few watt input power [28]. The efficiency was the world record for a long time.

A microwave source based on tubes is still a good device for narrow-beam WPT because of its high efficiency and power capacity. However, it is difficult to apply it for a narrow-beam WPT system to a moving target because we need a beam forming system. The microwave tube is not suitable for beam forming. People require a high-efficiency WPT system, even for the moving target in narrow-beam WPT. To solve the conflicting requirements of high efficiency and chasing a target, beam forming by the phased array system is essential. After the 1980s, the trend of the narrow-beam WPT moved to the development of the phased array system. Higher frequency WPT systems were simultaneously developed from the 1980s to increase beam efficiency, which is decided by the Friis transmission formula.

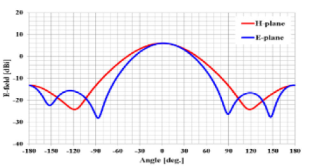
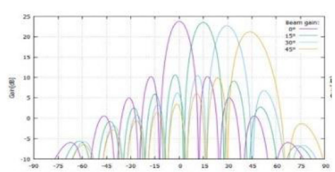
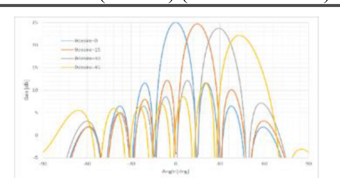
In Japan, Hiroshi Matsumoto at Kyoto University led narrow-beam WPT research since the 1980s [4]. He succeeded in the first narrow-beam WPT experiment to a small flying airplane with a 2.411 GHz phased array system in 1992. He also developed some retrodirective WPT systems in the 1980s and 1990s. His aim was mainly an SPS (Solar Power Satellite), and he performed the first WPT experiment in space with a magnetron in 1983 and the second with a phased array system in 1993, respectively. He also developed an SPS demonstrator with a phased array at 5.8 GHz. His technologies are linked to not only the SPS but also the commercial applications of wide-beam WPT in Kyoto University now. Japanese Ministry of Economy, Trade, and Industry (METI) is interested in the SPS and WPT via microwave and conducted some WPT field experiments in 2015 and 2019.

After the 2010s, a lot of narrow-beam WPT field experiments have been conducted not only in Japan but also in China and Korea. Kwan-Ho Kim of Korea Electrotechnology Research Institute started a research project on narrow-beam WPT in 1997, and his group succeeded in the 50-m WPT field experiment at 2.45 GHz in 2000. Transmitted microwave power from a magnetron was 2.3 kW, and the received DC power was 1.02 kW. In China, Changjun Liu's group at Sichuan University performed a 4.5-m short-distance microwave power beaming experiment whose overall efficiency reached 14.2% in 2014. In 2020, the research group of Xing Chen, Sichuan University, designed and implemented a microwave power beaming system at 5.8 GHz. The experimental transmission distance was 10 m, and the overall transmission efficiency of the microwave wireless energy transmission system was 18.5%. In Wuhan, China, Long Xiao of China Ship Development and Design Center developed a special microwave/millimeter tube at 35 GHz for the transmitter and a new GaN diode for the rectenna. An experiment was conducted over a 300-m transmission distance in 2020. The

TABLE 2. Future WPT System Scenario for the New WPT RR in Japan (2019–20) [23]

	920MHz-Band	2.4GHz-Band	5.7GHz-Band
Circumstance	Factory (Indoor), Nursing Home, etc.	Factory (Indoor), Plant, Garage, etc.	Factory (Indoor), Plant, Garage, etc.
Purpose	Wireless power supply for sensor network	Wireless power supply for sensors, small display, etc.	Wireless power supply for sensors, small display, etc.
Method	Wide area including out-of-sight and simultaneous WPT for multi-users by omnidirectional antenna or by wide beam	One-to-one WPT with cheap receiver by beacon signal that uses wireless LAN which is collaborated with conventional system	Equivalently one-to-one WPT of high power and long time by change of beam direction from transmitter which is finely controlled by special receiver
Number of receivers per one transmitter	5–10 (Simultaneous)	1–several dozens (Sequential)	1–several dozens (Sequential)
Required Power from user	A few mW–a few hundred mW	App. 50 mW–app. 2W	A few mW – a few hundred mW
Tx-Rx distance	<5 m	<10 m	<10 m
WPT when human is	Possible (under radio wave safety level)	Non-permission	Non-permission

TABLE 3. Parameters for Electromagnetic Interference Evaluation for Discussion of New WPT-RR in Japan (2019-20) [23]

	920MHz-Band	2.4GHz-Band	5.7GHz-Band
Tx power	1W (30dBm)	15W (41.8dBm)	32W (45.0dBm)
Frequency	918.0, 919.2 MHz	2412, 2437, 2462, 2484 MHz	5740, 5742, 5744, 5746, 5748, 5750, 5752, 5758, 5764 MHz
EIRP	Max. 36 dBm	Max. 65.8 dBm	Max. 70.0 dBm
Bandwidth	200 kHz	No definition	No definition
Tx Antenna gain	6.0 dBi	24.0 dBi	25.0 dBi
Height of Tx antenna	Indoor (2.5 m above floor)	Indoor, at ceiling, direction of antenna is down (to floor) (4.5 m above floor)	Indoor, at ceiling, direction of antenna is down (to floor) (5 m above floor)
Directivity of Tx antenna (front is down direction for 2.4GHz and 5.7GHz system)	 -90° 90°	 -90° 90°	 -90° 90°
Applied place	Indoor WPT Occupational exposure, WPT General public exposure	Indoor WPT Occupational exposure	Indoor WPT Occupational exposure
Modulation	No definition	No modulation and Continuous Wave	No modulation and Continuous Wave
Loss via wall	10.0 dB	14.0 dB	16.0 dB

major aim of the Chinese development of the narrow-beam WPT is the SPS.

B. KEY TECHNOLOGY OF NARROW-BEAM WPT: BEAM FORMING

Beam forming technology can solve the conflicting requirement of high efficiency and chasing a target for narrow-beam WPT. Beam forming is originally based on remote sensing technology and/or Multi-In Multi-Out technology for wireless communication. They are basically the same. However, WPT requires a high-efficiency microwave transmitter and highly accurate beam forming. Cost and size are also important.

Recently in Japan, a new phased array system with new solid-state devices is being developed for SPS applications. METI supported the project, and Mitsubishi Electric Corp. developed new GaN HEMT devices and thin and highly accurate phased array systems in 2015 [29]. J-Space Systems managed the project. First of all, they developed a new GaN HEMT and monolithic microwave integrated circuit (MMIC) F-class high-power amplifier at 5.8 GHz (Fig. 6). Power add efficiency reached 70% with 7 W output power.

The developed MMIC can reduce the size of a phased array system and can achieve high efficiency. Fig. 7(a) is the structure of the transmission module. One sub-array has 4 antenna

TABLE 4. **Agreed Technical Condition of the New WPT RR in Japan [23]**

	920MHz-Band	2.4GHz-Band	5.7GHz-Band
Frequency band	917.8 MHz–919.4 MHz	2410 MHz–2486 MHz	5738 MHz–5766 MHz
Chanel	918.0 MHz, 919.2 MHz	2412 MHz, 2437 MHz, 2462 MHz, 2484 MHz	5740 MHz, 5742 MHz, 5744 MHz, 5746 MHz, 5748MHz, 5750 MHz, 5752 MHz, 5758 MHz, 5764 MHz
Tx/Communication method	Unidirectional communication, simplex, duplex, half-duplex, Broadcast communication	Unidirectional	Unidirectional
Modulation	No definition	No modulation and Continuous Wave	No modulation and Continuous Wave
Wireless communication between Tx and Rx	No definition	No definition	No definition
Beacon Signal from Rx	No definition Use the other wireless communication	No definition Use the other wireless communication	Same frequency with Tx by instruction from Tx of specified small electric power radio station etc.
Transmitter Box	RF and modulation systems are Locked and cannot be open.	RF and modulation systems are Locked and cannot be open.	RF and modulation systems are Locked and cannot be open.
Tx antenna	No definition	Beam directional antenna by beam forming	Beam directional antenna by beam forming
Applied place	WPT Occupational exposure or WPT General public exposure	WPT Occupational exposure	WPT Occupational exposure
Allowable deviation of frequency	$< \pm 20.0 \times 10^{-6}$	$< \pm 50.0 \times 10^{-6}$	$< \pm 20.0 \times 10^{-6}$
Allowable value of occupied bandwidth	< 200 kHz	No definition	No definition
Leakage power to adjacent channel	< 10dBm at edge of channel, < 0.5dBm of leakage power to adjacent channel	No definition	No definition
Tx power	<1 W	<15 W as sum	<32 W as sum
Tx antenna gain	<6 dBi but Tx antenna gain can be supplied up to a decreased value when EIRP is below 36 dBm	<24 dBi but Tx antenna gain can be supplied up to a decreased value when EIRP is below 65.8 dBm	<25 dBi but Tx antenna gain can be supplied up to a decreased value when EIRP is below 70.0 dBm
Directivity of Tx antenna	No definition	Capable of beam forming and control at will. However, the capability of beam direction is only < 60 degree to the ground	Capable of beam forming and control at will. However, the capability of beam direction is only < 60 degree to the ground
Allowable value of EIRP	No definition	<47 dBm/MHz in 80-90 degree to ground	<47 dBm/MHz in 80-90 degree to ground
Allowable deviation of Tx power	Upper limit 20%, lower limit <80%	Upper limit 20%, lower limit <50%	Upper limit 20%, lower limit <50%
Receiver	< -54 dBm/100 kHz in <930MHz (except 915 MHz – 930 MHz) as unwanted re-radiation from Rx, <-47 dBm/MHz in >1.215 GHz	No definition	$< \pm 20.0 \times 10^{-6}$ as allowable deviation of frequency. Allowable value of unwanted re-radiation is shown in Table 4.3.2 <0.32 mW as Rx power (upper limit 20%, lower limit <50%) <0 dBm as EIRP
License	unnecessary	necessary	necessary

elements and one high-power amplifier. Sub-arrays are connected by a beam forming network (BFN). Fig. 7(b) indicates a transition module. Its size is 60 cm × 60 cm, its thickness is only 2.5 cm, and its weight is 16.1 kg. The average maximum power is 449.8 W. The power-to-weight ratio is 35.8 g/W only. The total DC-RF efficiency, including a high-power amplifier, a driver amplifier, BFN, and an isolator, is 35.1% as a system. The final configuration with 4 modules is shown in Fig. 7(c). They keep the development of the phased array system for the narrow-beam WPT supported by METI now.

JAXA collaborated with J-Space Systems. They carried out an estimation experiment of the accuracy of beam forming with the developed phased array system in 2015. JAXA is also interested in the SPS. In the system, they combined beam

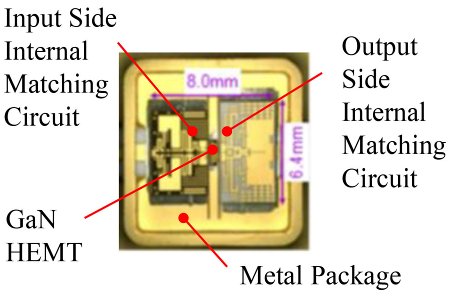


FIGURE 6. **Developed MMIC F-class high-power amplifier with GaN HEMT at 5.8 GHz [29].**

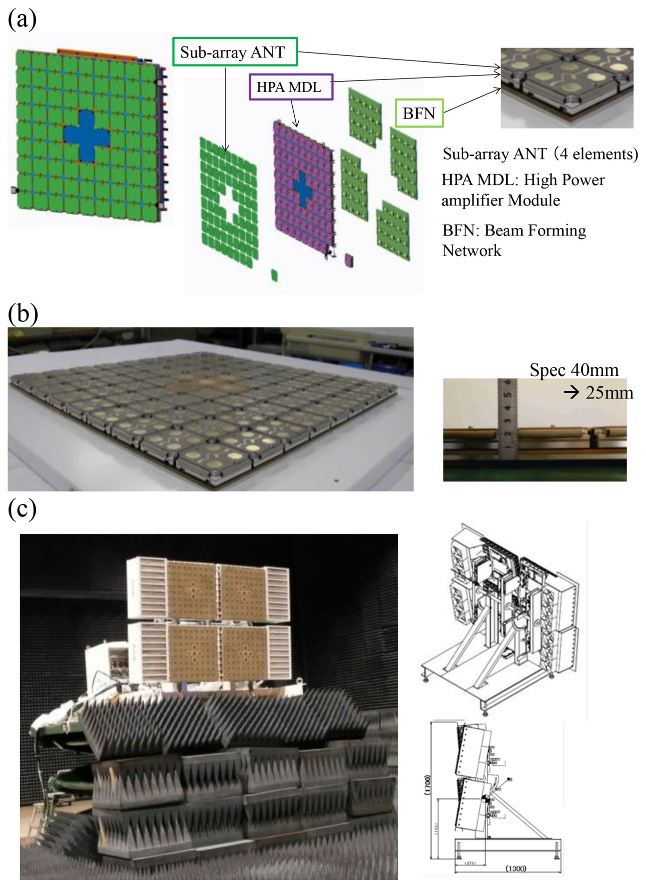


FIGURE 7. **Developed thin-phased array system with GaN HEMT at 5.8 GHz (a) Structure of transmission module (b) Transmission module whose thickness is <2.5 cm (c) Phased array system with 4 modules for narrow-beam WPT.**

forming and target detection. One is an amplitude mono pulse method with a beacon signal, and the other is a rotating element electric field vector method. They measured the error of beam forming with 4 modules (120 cm × 120 cm). The measured RMS (root mean square) was 0.147 degree [30]. It was very close to the calculated RMS of 0.13 degree. It has sufficient accuracy when we consider the future SPS system whose transmitting antenna diameter will be over 2 km and the required accuracy of beam forming up to 0.001 degree

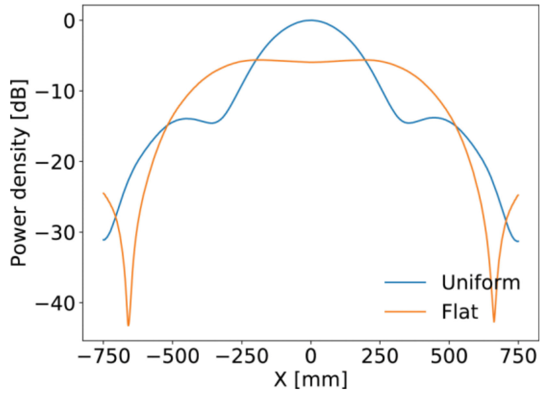


FIGURE 8. **Normalized near-field beam patterns (FDTD simulation) at 1.2 m distance of flat-top beam and beam pattern (uniform) excited by uniform amplitude tapering of transmitting antenna. Transmitting array size is 510 × 510 mm at 2.45 GHz [34].**

for a transmission distance of 36,000 km. In Japanese SPS design, beam efficiency of narrow-beam WPT in 36,000km is estimated 96.2% with 1.93kmϕ transmitting antenna and 2.45kmϕ receiving antenna at 5.8GHz without loss in air, rain, and ionosphere. The total transmitting microwave power is greater than 1.3GW from more than 2 billion antenna elements of a phased array in the Japanese SPS

To be the same as hardware of the beam forming, software of algorism of the beam forming is very important for the narrow-beam WPT. Theoretically, the beam efficiency between a transmitting antenna and a receiving antenna is calculated by the Friis transmission formula, and it is a limitation for beam efficiency. Amplitude tapering at the transmitting aperture antenna is often adopted to increase the beam efficiency, such as Gaussian tapering. However, when we consider the total efficiency of the WPT, including beam efficiency, the DC-RF conversion efficiency of a transmitting circuit/system and RF-DC conversion efficiency of a receiving circuit/system, the amplitude tapering is not the best because DC-RF or RF-DC conversion efficiency of the circuit decreases because of the amplitude tapering both at the transmitting and receiving antennas.

We, Kyoto University, proposed a new tapering model both to increase the beam efficiency and keep high DC-RF conversion efficiency for microwave amplifiers at the transmitting antenna [31], [32]. Recently, we also propose a novel flat-top beam in the radiative near field (Fresnel region) in consideration with the RF-DC conversion efficiency of a rectenna array (Fig. 8) [33], [34]. In this case, the DC-RF conversion efficiency of microwave amplifiers is not the best.

Conventional narrow-beam WPT, especially for the SPS, adopts a retrodirective method for target detection. Recently in Japan, a new retrodirective method has been proposed for more effective narrow-beam WPT. It was named the both-sides retrodirective system for minimizing the leak energy [35]. In the conventional hardware retrodirective system, the phase conjugate circuits were adapted only at the transmitting

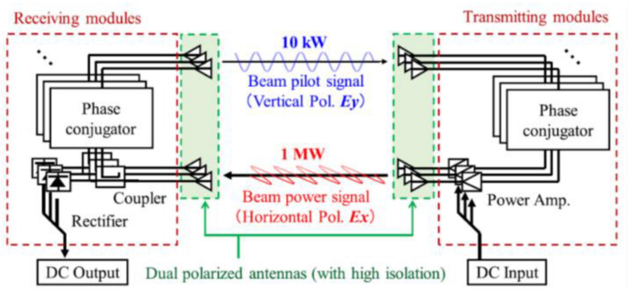


FIGURE 9. Block diagram of a both-side retrodirective system [32].

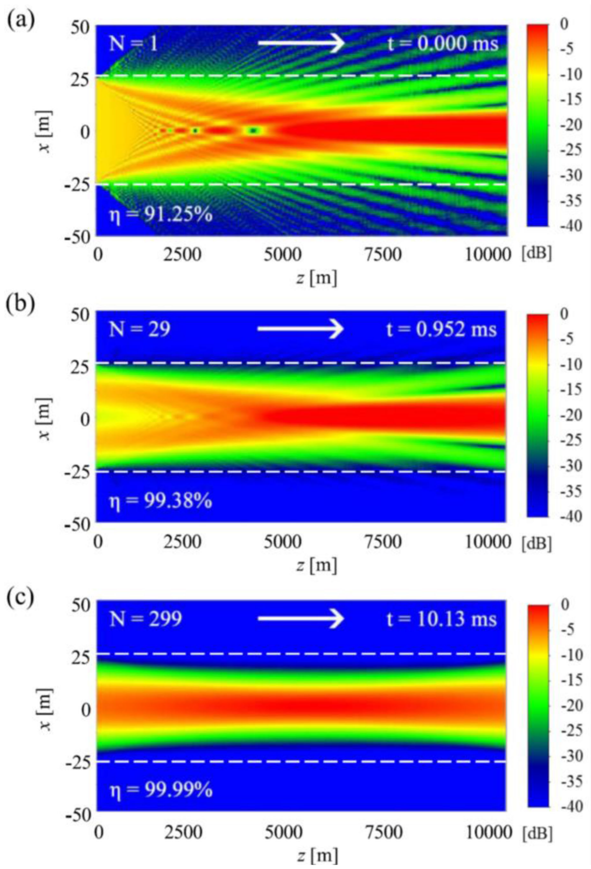


FIGURE 10. Beam profile of the pilot signal at each number of propagation (a) N = 1, (b) N = 29, (c) N = 299 (N is the number of iteration) [32].

array antenna, and the beacon signal from a target usually becomes a plane wave after propagation to the transmitting antenna. In this system, the retrodirective operations are repeated between the transmitting and receiving antennas by the beamed (sphere wave) beam signal (Fig. 9). In this system, the beacon signal and narrow power beam are transmitted to each other, and the phase conjugation is iterated. Fig. 10 indicates the simulation results of the both-side retrodirective system after iteration. As a result of the iteration of the phase conjugation, the WPT beam is converged to maximize the beam efficiency at last.

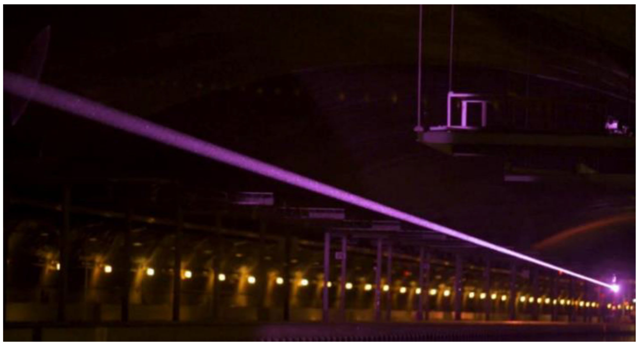


FIGURE 11. LPT demonstration in Maryland, US, on May 23, 2019 [40].

C. INNOVATION OF NARROW-BEAM WPT

For narrow-beam WPT, a phased array is one of the most important technologies. However, even if we develop excellent phased array and beam forming algorism, the beam efficiency is theoretically limited by the Friis transmission formula. By the Friis transmission formula, higher frequency is better to focus wireless power at one target and increase the beam efficiency. However, when frequency increases, the number of antenna elements in the array antenna increases and the efficiency and power of the device and circuit decrease. We can develop better device and circuit with innovative technology. So recently, narrow-beam WPT system with higher frequency is developed.

As shown in Section 2, a narrow-beam WPT field experiment at 35 GHz with a developed millimeter-wave tube and developed GaN diode for a rectenna was carried out in Wuhan in China. There are good rectennas at W-band developed in the world. National Central University's group in Taiwan developed a dual-band, 35 and 94 GHz rectifier with 0.13 μm CMOS technology in 2010 [36]. The measured power conversion efficiencies were 53% and 37% in free space at 35 and 94 GHz, respectively. A group at Tel Aviv University, Israel, also developed a W-band (75–110 GHz) rectifier within 65-nm CMOS technology, and measured efficiency was approximately 2% [37]. In École Polytechnique Montréal, Canada, a 94 GHz rectenna with GaAs SBD was developed in 2015, and the measured efficiency was 37.7% at 90 GHz and 32.2% at 94 GHz at 3 dBm input power [38]. Tsukuba University's group in Japan developed a 303 GHz rectenna with 2.17% efficiency for 17.1-mW output DC power with commercial GaAs SBD in 2018. They are developing a GaN SBD to increase the efficiency in sub-terahertz rectennas since 2019 [39]. They adopted Gyrotron as a transmitter for measurement. The millimeter-wave and sub-terahertz rectifier technology are advanced. We expect a good transmitter with a solid-state device for a phased array in higher frequency with high DC-RF conversion efficiency and accuracy.

When we need higher beam efficiency and smaller antenna aperture, the ultimate WPT is a laser power transfer (LPT) system. Naval Research Laboratory in the US succeeded in the LPT between two 13-foot-high towers (325 m distance) in

May 2019 [40]. Transmitted laser power was 2 kW. The receiver is a specially designed photovoltaic. The laser beaming 400 W from the transmitter to the receiver was invisible to the naked eye. The project aims to build an SPS. here is no radio wave regulation for laser, not only in WPT but also in all laser applications, except for the safety regulation..

D. DISCUSSION STATUS OF REGULATION OF NARROW-BEAM WPT

In ITU-R report SM.2392, the narrow-beam WPT applications are mentioned, e.g., WPT to move/fly target, point-to-point WPT, wireless charging for electric vehicles, and SPS. However, here we mainly focus on wideband WPT in the ITU-R, and the discussion of the narrow-beam WPT will be the next.

In Japan, a research project named Cross-ministerial Strategic Innovation Promotion Program (SIP) was executed to develop a new WPT system in November 2018. In the SIP project, both basic research and WPT application development are involved. As one of them, the narrow-beam WPT system to fly a drone at 5.8 GHz is developed by Mitsubishi Electric Corp. and Kyoto University under the leadership of Tokyo Electric Power Company Holdings.

In addition to the R&D, Kyoto University is searching for the harmonization method for narrow-beam WPT whose power is higher than wide-beam WPT in the SIP. Some methods can be used to reduce interference to a conventional wireless application, such as frequency division duplex (FDD), time division duplex (TDD), space division duplex (SDD), and code division multiplexing (CDM). Adopting FDD, which means we can obtain special frequency for WPT, is ideal; however, it is difficult in reality. Unfortunately, it is hard to apply CDM because conventional WPT is based on no modulation.

First of all, we estimate the effect of TDD and SDD for narrow-beam WPT. For the TDD-WPT system, we assume pulse WPT to reduce time with high power and keep average wireless power. We assume the WPT system is at 5.8 GHz, which is at 140 ch of IEEE802.11a W56 of Wi-Fi, and the victim is Wi-Fi in the same frequency band. We estimate the harmonization condition in which Wi-Fi keeps up to -10% throughput when the duty ratio of the pulse WPT changes. Figure 12 indicates one of the measurement results. There is a harmonization condition of the WPT power and duty ratio of the pulse. We also found that pulse WPT can increase RF-DC conversion efficiency [41]. So pulse (TDD) WPT is one of the promising systems to harmonize the conventional wireless system. As a next step, we consider other candidates, such as dedicated short-range communications at the same band, and we also try to consider the SDD system, which is suitable for narrow-beam WPT. Based on the measurement data, we expect future discussions for the new RR of narrow-beam WPT in Japan and the world.

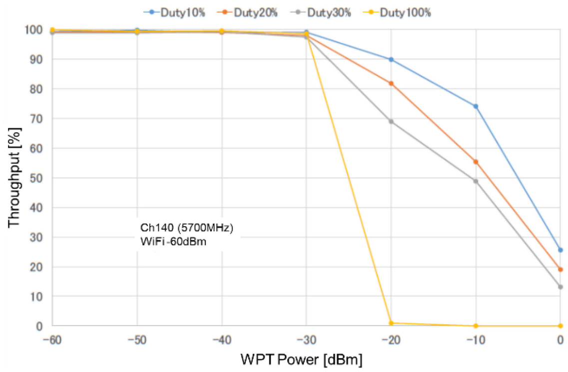


FIGURE 12. Measured Throughput of Wi-Fi when WPT power and duty ratio of pulse change.

IV. CONCLUSION

The WPT has a long history; however, it started from born of killer WPT applications, active research and development at universities in 20th century, and new WPT businesses in the 21st century. First of all, wide-beam WPT based on the conventional wireless system is exciting. A lot of innovation are recently born and new WPT startup companies are born. Based on recent innovation of the wide-beam WPT, we hope to reach new radio regulation soon and new WPT business will be expanded. Next, we expect narrow-beam WPT instead of a power line. Unfortunately, we have not reached new business and regulation of the narrow-beam WPT. However, expansion of the wide-beam WPT application push the technology of the narrow-beam WPT and discussion for new regulation.

We can draw a future in which electricity is like air with the far-field WPT. The wireless power will be most important but no reorganization like the air. with WPT technology. I hope you share the future of the WPT world.

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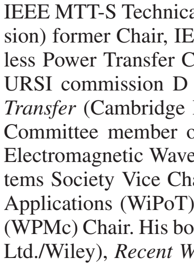

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