High-Power Simultaneous Wireless Information and Power Transfer System Based on an Injection-locked Magnetron Phased Array

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***Abstract*—We built a phased array system for high-power simultaneous wireless information and power transfer (SWIPT) using four 5.8-GHz injection-locked magnetrons. In the magnetron injection-locked state, the transmission efficiency was measured at different modulation rates. The fluctuation in the transmission efficiency was not more than 0.5%. We observed that dynamic beamforming does not affect communication quality. Using the magnetron phased array system, SWIPT experiments revealed that a frequency modulated (FM) signal that carries a video camera signal is transmitted and decoded during dynamic beamforming. In this SWIPT system, the main lobe transfers power, and information can be demodulated in front of the magnetron phased array from −90º to 90º. The maximum transmitted microwave power of the proposed system is 1637 W.**

***Index Terms*—Magnetrons, injection-locked oscillators, phased arrays, phase shift keying, modulation, wireless power transfer**

I. Introduction

THE applications of wireless communication via microwaves is rapidly increasing, and wireless charging technology via microwaves has attracted attention for applications in wireless powering sensors, mobile devices and drone charging, etc. [1]–[4]. The broadcast wave can also be harvested [5]. A new domestic radio regulation of three microwave frequency bands for far-field wireless power transfer (WPT) has been employed in Japan [6]. It is the first far-field WPT standard for commercialisation. In the USA, Energous Corp. and Ossia Inc. received Federal Communications Commission (FCC) authorisation for WattUp [7] and Cota [8] real wireless power systems, respectively. WPT via microwaves employs the same radiation method as the wireless information transfer (WIT). A simultaneous wireless information and power transfer (SWIPT) system improves spectrum resources and transmitter devices. Currently, SWIPT research has mostly focused on energy harvesting at low power levels [9]–[11]. However, the low received power level limits the applications of wirelessly charged devices. In another way, in the WPT system of charging flying drones, the WPT system can be used to amplify the WIT signal, such as sending a flight control signal.

In this study, we developed a high-power, low-cost and high-efficiency SWIPT system with injection-locked magnetrons. Compared with semiconductor amplifiers, magnetrons have a higher energy density, higher efficiency and lower cost but a less stable frequency and phase. In our previous study, we discussed how to control the phase and power of magnetrons [12]. Liu *et al.* developed two injection-locked magnetrons combining output microwave power reaches 26 kW with phase controlling [13]. Tahir *et al.* developed an injection-locked 2.45 GHz magnetron as a transmitter for communication and achieved the transmission of phase-shift keying (PSK) data of 2 Mbps [14]. It indicates that the magnetron behaves like an amplifier, and its output could follow the injection signal. Subsequently, we discovered that 2.45 GHz and 5.8 GHz continuous-wave magnetrons can be used to modulate the amplitude, phase and frequency by applying an injection-locked method [15]. Experimental studies of the injection-locked magnetron to power wireless TV have been reported [16]. These studies have proven that the injection-locked magnetron has good enough stability for WIT.

In the recent previous study, a phased array system with four phase-controlled magnetrons was built by applying the injection-locking and phase-locked-loop methods which demonstrated the properties of microwave beamforming [17]. The WPT efficiency (RF–RF–DC) of 11.97% was achieved at a distance of 5 m [17]. This letter presents a SWIPT system of magnetron phased array that transfers modulation microwaves with beamforming. We investigated the influence of the modulation signal on the power transmission efficiency for WPT, and the effect of the dynamic beamforming on the communication quality. We conducted a SWIPT experiment to verify the transfer of modulation signals using dynamic beamforming.

II. Design of The Injection-locked Magnetron Phased Array

An injection-locked magnetron phased array was combined with four injection-locked magnetrons serving as amplifiers (Fig. 1). The layout of the magnetrons was set as 2 × 2

Manuscript received May 31, 2021; revised July 29, 2021, accepted August 11, 2021.This research was supported by the research grant programme of the Futaba foundation, the Japan Society for the Promotion of Science, Grant-in-Aid for JSPS Fellows 19J12459, the collaborative research program: Microwave Energy Transmission Laboratory (METLAB), Research Institute for Sustainable Humanosphere, Kyoto University.

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arrangement which obtains 2D beamforming. A modulated signal, rather than a sine wave in a previous study [17], was divided into four ways and sent to four phase shifters, then amplified to 10 W and transmitted to the injection-locked magnetron. The magnetron phased array works at a frequency of 5.788 GHz, and the larger injection power is, the wider the injection-locked range reaches. Each injection-locked magnetron is connected to a slot array antenna having 112 slots and dimensions of 494 mm × 290 mm × 40 mm. The total gain of the phased array was 29.2 dBi. The phase shifters were used to control the microwave beam direction with a scanning range of ±3° in horizontal directions [17]. The output power of the magnetron phased array can be controlled from 350-1637 W.

To keep the magnetron phased array working in the injection-locked state, the modulation bandwidth must be narrower than the injection-locked range. In the initial state, the phase difference of the four magnetrons is set at ±1º to ensure that the beam direction is at the centre of the antenna. In this system, the injection-locked magnetrons work as amplifiers without the phase-locked loop, which is different from the previous study [17]. The phase-locked loop can make the magnetron a phase-controllable microwave source; however, its response time is about 50 μs [12], which limits the possibility of high modulation rates.

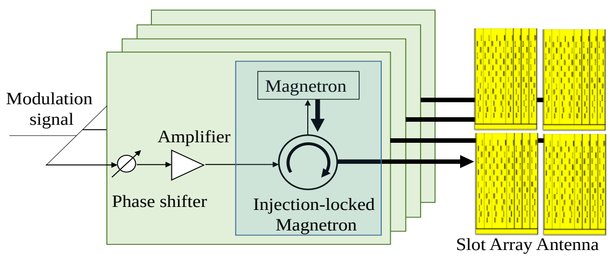

Fig.1 Block diagram of the magnetron phased array system.

III. Effect of WIT and WPT

The effects of WIT and WPT on the injection-locked magnetron phased array were evaluated. The transmission efficiency is a key parameter for a WPT system. First, the transmission efficiency $\eta_{RF\text{–}RF}$ was measured at different modulation rates. Second, the impact of beamforming on communication quality was also investigated. The pseudo-noise (PN9) sequence modulation signal and error vector magnitude (EVM) of the received signal were used to evaluate the communication quality. The experimental devices were set in an anechoic chamber.

A. *Modulation effects on WPT*

The magnetron phased array and a 5.8-GHz rectenna array (IHI Aero Space) [18] were set for WPT experiments [17] at a distance of 5 m. The magnetron phased array transmitted 5.788-GHz microwave power, and the rectenna array outputted dc power P_{DC}. A signal generator (Keysight N5172B) output a quadrature phase-shift keying (QPSK) signal as the modulation signal shown in Fig. 1. Other parameters of the signal generator were set as (filter: root raised cosine; Alpha/BT: 0.35). The rectifier efficiency $\eta_{RF\text{–}DC}$ of the rectifiers varied less than 0.5% from 5.780 to 5.789 GHz at a fixed power. The microwave power P_{RF}, dc power P_{DC} and efficiency $\eta_{RF\text{–}RF\text{–}DC}$, combining the transmission efficiency $\eta_{RF\text{–}RF}$ and rectifier efficiency $\eta_{RF\text{–}DC}$, were measured at different modulation rates (1, 10, 100 and 1000 kbps). Table I lists the measurement results. The degradation of P_{DC} by modulated wireless power transfer was less than 3% compared to the non-modulated wireless power transfer. The WPT experiment revealed that the magnetron phased array transferring modulated signals (≤1 Mbps) does not affect the transmission efficiency significantly.

TABLE I
WPT experiment result of the modulation phased array

Rate	0 bps	1 kbps	10 kbps	100 kbps	1 Mbps
P_{RF} (W)	1409	1405	1406	1405	1406
P_{DC} (W)	142.0	137.8	141.5	140.8	140.2
$\eta_{RF\text{-}RF\text{-}DC}$	10.07%	9.80%	10.06%	10.01%	9.96%

B. *Effects of beamforming on WIT*

Fig. 2 shows the WIT experimental setup for measuring EVM. The receiving antenna was set at 22.5°, which is designed at the centre of the main lobe of the magnetron phased array [17]. It was connected to a signal analyzer (Agilent N9010A VSA89601) to measure the parameters. The phase shifters were set for dynamic beamforming at ±2º degree per 100 ms, which is nearly the response time of the magnetron phased array.

The measured EVM and other parameters are listed in Table II. The parameters of the dynamic and static beams were all lower than 6%. At angles of −90° to 90°, EVM was measured at a similar level. The values were mainly affected by the received power level. Therefore, attenuators were used to adjust the received power level. The received power was measured with the power level at −55 dBm (*EVM*: 5.21%, *Mag Err*: 3.83%, *Phase Err:* 2.03°, *Freq Err:* −1.26 kHz, *SNR*: 25.66 dB) and 65 dBm. (*EVM*: 8.15%, *Mag Err*: 6.06%, *Phase Err*: 2.97°, *Freq Err*: −1.23 kHz, *SNR*: 21.58 dB). *Freq Err* shows the carrier's frequency error relative to the centre frequency (LO frequency). Here, *Freq Err* are mainly affected in different *LO* frequencies of the signal analyzer and the signal generator (Keysight N5172B). We found that the communication quality is mainly affected by the strength of the received signal. However, in the WIT experiments, when the beam rate (10 Hz) of the phased array was much lower than the modulation rate (1 MHz), the beamforming showed little effects on the communication quality.

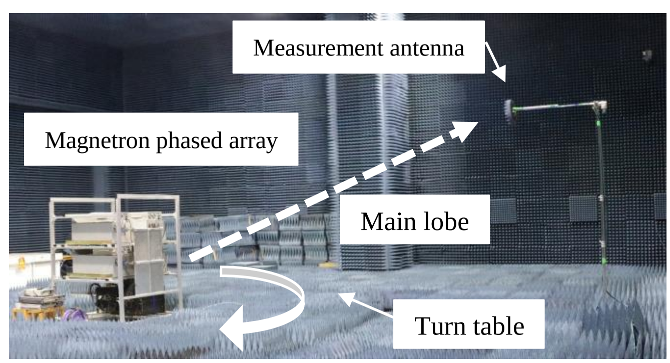

Fig. 2 Photo of the magnetron phased array system for measuring error vector magnitude.

TABLE II
Parameters of the WIT experiment results.

Angle	Static beam					Dynamic beam				
	EVM	Mag Err	Phase Err	Freq Err	SNR	EVM	Mag Err	Phase Err	Freq Err	SNR
	rms	rms	deg	kHz	dB	rms	rms	deg	kHz	dB
−90º	5.78%	4.23%	2.27	−1.22	24.76	5.25%	3.81%	1.98	−1.24	25.57
−72º	5.48%	3.96%	2.18	−1.21	25.21	5.21%	3.90%	1.99	−1.24	25.66
−54º	5.09%	3.57%	2.08	−1.20	25.87	5.16%	3.98%	1.88	−1.24	25.75
−36º	5.60%	4.18%	2.14	−1.20	25.03	4.68%	3.39%	1.85	−1.25	25.59
−18º	5.82%	4.44%	2.17	−1.20	24.69	5.01%	3.70%	1.94	−1.24	26.00
0º	5.44%	3.99%	2.12	−1.19	25.29	5.35%	3.76%	2.19	−1.25	25.43
18º	5.42%	3.95%	2.13	−1.19	25.30	5.22%	3.90%	2.00	−1.25	25.64
36º	5.20%	3.76%	2.07	−1.19	25.67	5.13%	3.81%	1.98	−1.25	25.80
54º	5.34%	4.01%	2.03	−1.19	25.45	5.07%	3.75%	1.97	−1.26	25.90
72º	5.39%	4.00%	2.07	−1.19	25.37	5.25%	3.86%	2.05	−1.26	25.59
90º	5.41%	4.04%	2.06	−1.18	25.34	5.21%	3.83%	2.21	−1.26	25.66

IV. SWIPT EXPERIMENTS

We experimented to verify that a modulation signal can be transferred by the phased array via beamforming. We built a SWIPT system using a magnetron phased array system. The block diagram of the system is shown in Fig. 3. A frequency modulator (Pakite, PAT-630 transmitter) was used to modulate the camera signal on the 5.790-GHz channel. The FM signal was divided to feed four phase shifters used for beamforming. The beamforming signals were controlled using a LabVIEW programme via an analogue unit (NI9263). The programme also controlled the magnetron power supply. Each injection signal in the phase shifter via the amplifier (R&K CA5800BW50-4040R) was injected into the magnetron. At the receiver, we set up two rectenna to confirm the beam deflection. The rectenna is composed of the receiver antenna, microwave rectifier circuit and LED load. The LED could display when the rectenna was irradiated with a 5.8-GHz band microwave [17]. A TV was used to show the video camera signal. The frequency demodulator (Pakite, PAT-630 receiver) received the FM signal and decoded it to a TV.

After keeping the magnetron phased array output power for nearly two minutes, the filament power supplies of the magnetron were turned off to keep the spectrum pure. The FM signals were amplified to 10 W, which is high enough to lock the magnetron frequency range larger than the FM modulator bandwidth (from 5.788 to 5.790 GHz). When four magnetrons worked in the injection-locked state, the TV in the receiver successfully displayed the video signal of the camera. Then, the phase shifter was controlled to form the microwave beam every 2 s. Rectenna 1 and 2 LED were observed that displaying in cycles. At the same time, and the TV still showed the camera signal in stable (Fig. 4). This verifies that the phased arrays transmitting a modulation signal and forming a beam can coexist. The experiment revealed a new method to build a high-power SWIPT system with magnetrons.

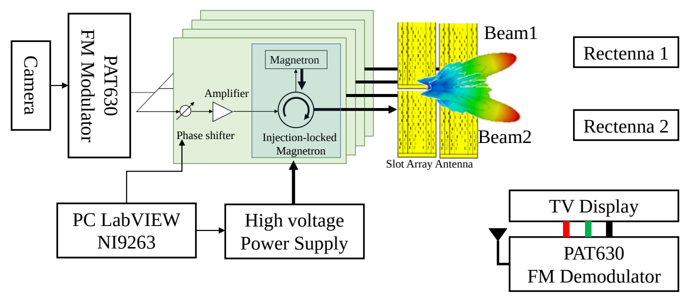

Fig. 3 Block diagram of the SWIPT experimental setup.

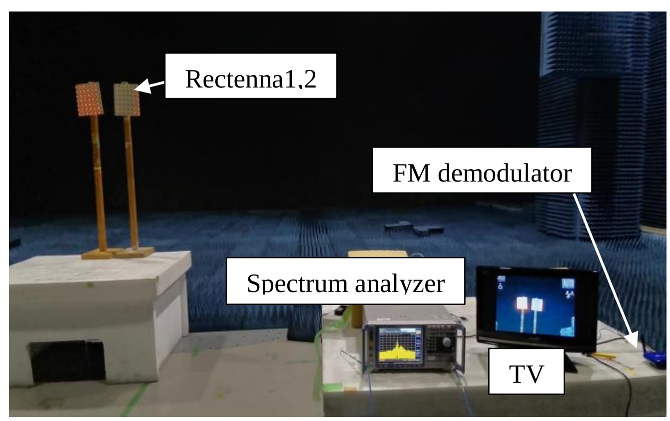

Fig. 4 Photo of the demonstration experimental setup.

V. CONCLUSION

A high-power SWIPT system was developed using a magnetron phased array system with four magnetron units. The experimental results reveal that the transmission efficiency and dynamic beamforming do not affect the modulation rate and communication quality, respectively. We hope to develop a high-power SWIPT system that can make more high-power-level devices work in power wirelessly.

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