Phase Synchronization Principle in 5.8 GHz Magnetron Phased Array

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***Abstract*— This paper analyzes the influence parameters of the phase control of the magnetron in detail and proposes a method to realize the frequency locking and phase synchronization of the magnetron. The noise-inhibition of the magnetron has made great progress in previous research, and the power and phase can be simultaneously controlled. Based on this principle, the phases of multiple magnetrons are synchronized and successfully applied to phased arrays. A 2×2 5.8GHz magnetron phased array was constructed with a maximum output power of 1680W and the beam-forming experiment of the magnetron phased array was demonstrated for wireless power transfer.**

Keywords—magnetron, phase-locked loop, phased array, injection-locking, beam forming, wireless power transfer

I. INTRODUCTION

High-power microwave systems are mainly composed of Klystron, Traveling Wave Tube (TWT), Gyrotron, Magnetron, and crossed-field amplifier (CFA)[1-2]. Besides these microwave devices, the magnetron is the oldest and cheapest microwave tube in use today which is widely used as an unparalleled high-power oscillator. In particular, it is applied to microwave ovens and radar. Even before the widespread use of microwave ovens, high-frequency dielectric heating has been used in industrial fields such as drying and bonding wood. Compared with other vacuum tubes, the magnetron has advantages including high efficiency, lightweight, and low cost. Although semiconductor devices (GaN HEMT) have been tried for high-power applications, they can't reach the magnetron's high output, high efficiency, and low-cost characteristics yet. Magnetron has the disadvantages of high noise, short lifetime, and narrow bandwidth.

Using magnetron for wireless power transfer (WPT). have been developed for nearly 50 years [3-5], one of the magnetron WPT system application is a grand plan called space solar power station (SSPS) [6]. SSPS proposed that solar panels use sunlight to generate electrical energy in the geostationary orbit (at an altitude of 36,000 km), and then supply it to the ground through microwaves. The SSPS also faces a problem, how to send tens of thousands of tons of SSPS to space orbit at low cost. Here, the microwave transmitters as the key unit of the SSPS, the large phased array elements should be lightweight with high power density and phase controllability. Considering weight, efficiency, and cost, the 5.8 GHz magnetron is the optimum microwave device.

A 5.8 GHz magnetron phased array was constructed as the microwave transmitter toward the realization of SSPS. The key technology of the magnetrons worked for microwave transmitter is how to control the magnetron output with a stable frequency and phase. In this study, the injection locking method to achieve a stable frequency and the phase-locked loop method by controlling a phase shifter to lock the phase were utilized.

II. PHASE SYNCHRONIZATION PRINCIPLE OF THE MAGNETRON PHASED ARRAY

When the magnetron is manufactured, there are individual differences due to process errors, resulting in oscillation frequencies. The output frequency or phase of a magnetron can be changed by controlling one of the following parameters [7]: 1) anode current, 2) magnetic field, 3) filament power, 4) injection power and 5) reflective power.

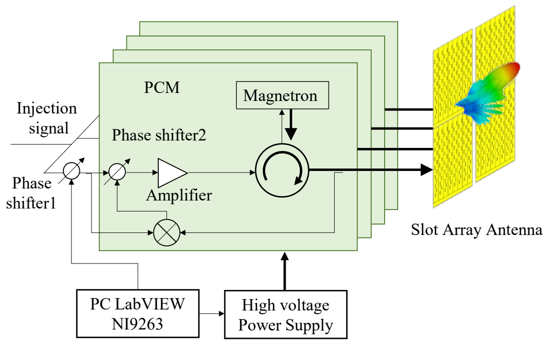

Fig.1 A schematic diagram of a magnetron phased array system [4].

We developed the power and phase-controlled magnetron (PCM) technology which uses injection power to lock the magnetron frequency and the anode current to lock the magnetron output power [8]. The phase control is realized by a phase-locked loop to follow the injection signal. Divided injection signals input several phase-controlled magnetrons and a magnetron phased array can be constructed. Figure1 shows a diagram of the phased array system. The injection signal which keeps the magnetron working at the same frequency inputs the magnetron via a circulator. According to the Adler equation [9], the larger injection power can achieve a wide locking bandwidth. However, there are individual differences in the oscillation frequency of the magnetron, and the power of the injected signal cannot be increased infinitely. Therefore, the short plunger of the magnetron launcher is used to adjust the operating frequency of the magnetron. This plunger can control the reflective power, which affects the magnetron output characteristics as shown in Fig.2. The short plunger is adjusted to ensure that all magnetrons in the phased array can achieve frequency locking under the same frequency. The PCM in Fig.1 also shows the phase-lock loop which is comparing the injection signal and output power via a mixer, the phase difference was fed back to the phase shifter 2, then the output phase can be locked with the injection signal phase. Adjusting the initial phase of each PCM to the same, the phases in the magnetron phased array are synchronized.

Magnetron anode current was used for controlling the output power which affects the frequency slightly as shown in Fig.3. The measured maximum output power of the magnetron phased array was 1680W when the anode current and voltage of each magnetron output are 187 mA and 3680 V, respectively. Phase shifters 1 were used for beam forming of magnetron phased array. Figure 4 shows the magnetron phased array beam-forming experiment. In horizontal directions, a beam scanning range of ±3 degree was obtained by adjusting phase shifters 1.

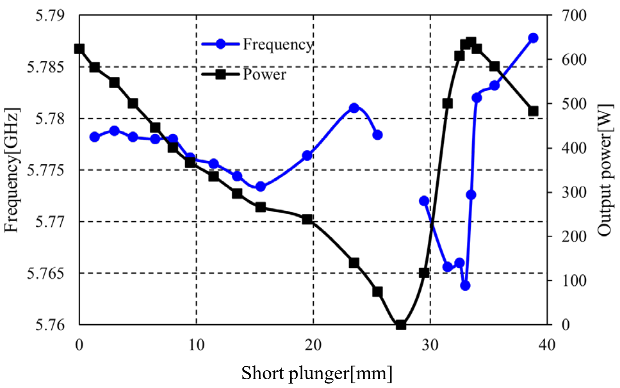

Fig.2 Magnetron output characteristics with reflective power.

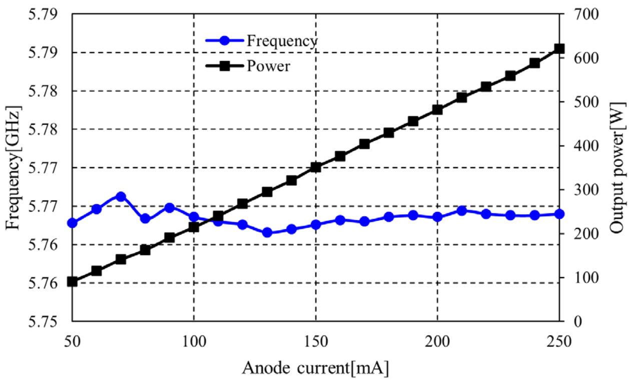

Fig.3 Magnetron output characteristics with anode current.

III. Conclusions

This paper introduced the phase synchronization principle of the magnetron phased array and demonstrated the beam-forming experiment. It is supposed to apply to the large-scale high-power microwave transmitting system.

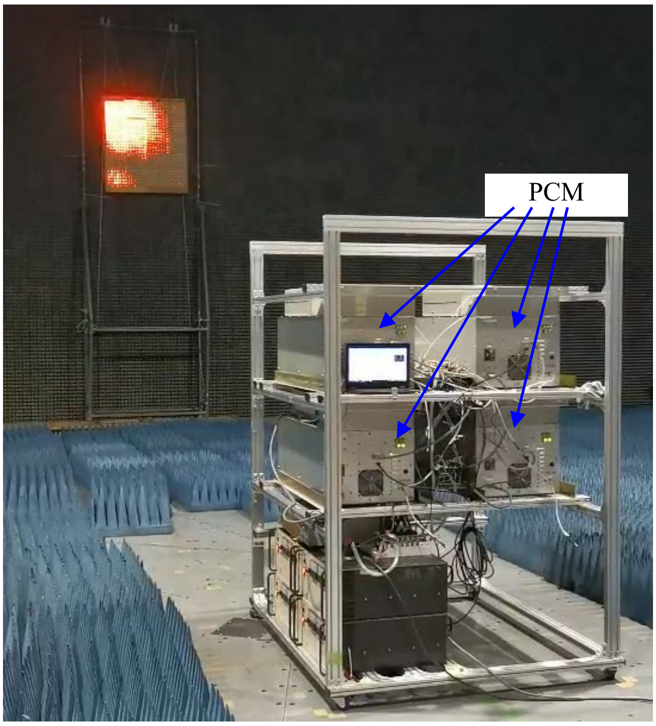

Fig.4 A photograph of the magnetron phased array beam forming demonstration experiment.

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