Progress of Microwave Power Combining Based on S-band Injection Locked CW Magnetrons

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***Abstract*—The progress of the microwave power combining systems based on S-band 20-kW continue wave (CW) magnetrons are presented, which is fulfilled at institute of applied electromagnetics, Sichuan University. A series of research and experiments about injection-locking and power-combining technique on magnetrons are conducted. The performance of injection-locked magnetron is improved and a power combining system with the output power of over 60.0 kW and combining efficiency of 91.5% is first realized. This system set a new performance record for S-band magnetron power combining systems for injection-locked magnetron with an output power of over 15 kW.**

Keywords—magnetron, power-combining, S-band, continuous wave, injection-locking

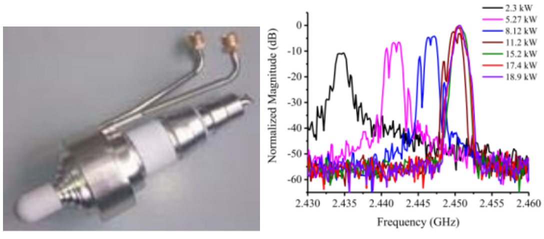
I. Introduction

High-power microwave have attached great interests of the researchers in fields such as microwave heating, wireless power transmission and chemical synthesis.[1] Magnetrons are widely used in industrial applications because of its low-cost, high-efficiency and compact size. But the output spectrum of magnetrons is noisy and the power capacity is restricted by its cavity size.[2]

Injection-locking technique is an effective method to improve and control the output of a magnetron. Based on injection-locked magnetron, magnetron high power-combing system is available. Power-combining technique is a solution to overcome the power restriction in single source system. This paper describes research and experiments implemented on injection-locked magnetron and power-combining system.

II. Injection Locking Magnetrons

In 2016, a 3-D particle-in-cell of a commercial industrial heating magnetron was developed for improving a fixed-output-power magnetron.[2] And the output power of a magnetron was continuously tuned from 2 to 19kW by adjusting its anode current for the first-time ever. In the injection-locking experiments, the locking-bandwidth was reduced from 11.7 to 2.4MHz when the output power



(a) (b)

Fig. 1. Magnetron and the output spectrum. (a) Water-cool 20kW CW magetron. (b) Magnetron output spectrum at various output power.[2]

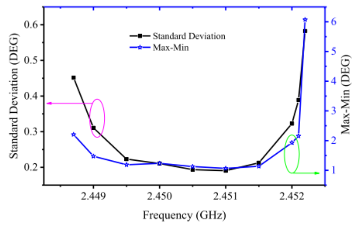


Fig. 2. Standard deviation and maximum peak-to-peak difference values as a function of the frequency of the injected signal. [3]

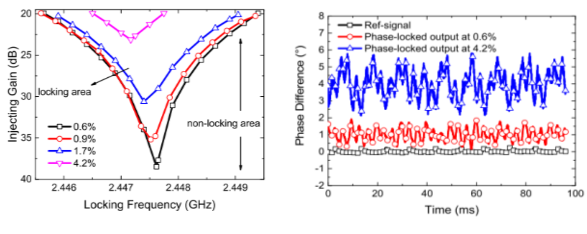
increased from 5 to 19.7 kW, and the injection power was kept constant at 120W. The phase and amplitude of the magnetron are controlled. The frequency pushing effect was observed in the experiment. The simulation and experiments were laying the foundation for coherent power combining.

In 2018, an experiment on phase deviation of 20 kW S-Band CW magnetron was carried out.[3] The phase deviation of a 20 kW injection-locked magnetron was studied for the first time. When the injected frequency is in the center of the locking range, the phase deviation is the best. When the output power of the magnetron is 19 kW and the injected power is 150 W, the phase deviation reduced from approximately 6˚to 1˚by frequency tunning.

In 2020, a 20 kW phase-locked magnetron was improved by anode voltage suppression [4]. When the voltage ripple of an injection-locked magnetron was varied from 4.2% to 0.6%, a nearly triple locking-bandwidth is realized, the locking-bandwidth increased from 1.54MHz to 3.95MHz. Besides, phase jitter of the injection-locked magnetron was converged from ±1.8˚ to ±0.9˚, and the phase noise at 100kHz was reduced from -57.27dB to -80.64dB.

III. Two-way Power Combining Systems

A two-way microwave power combining system was developed in 2015 [5]. Two 15kW CW magnetrons were used as the source. Fig. 4 shows the diagram of the system. The output phase was automatically adjusted by the computer. The best experiment combining efficiency is up to 96.7% with an output power of 26.3kW.



(a) (b)

Fig. 3. Measurement results. (a) Phase-locking areas with respect to the anode voltage ripples. (b) Phase jitters with respect to various anode voltage ripples.[4]

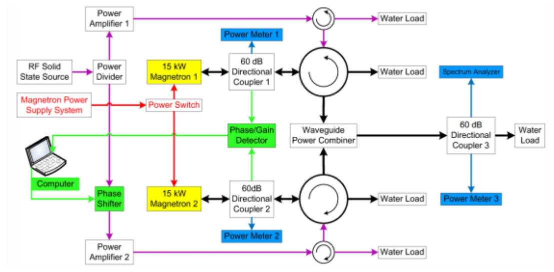


Fig. 4 The block diagram of two-way injection-locked 15 kW CW magnetrons microwave power combining system. [5]

A phase-shiferless power combining system with asymmetry injection was proposed in 2018 [6]. Fig. 5 gives the diagram of it. The system contained two 20 kW CW 2.45GHz magnetrons. It achieved an output power of 34 kW with a total combining efficiency of 86.7%. a spur suppression ratio of -65.0@500kHz, an output power stability of 0.02dB and a phase jitter of ±0.9˚. And in 2021, a low noise dual-way power combining system was conducted [8]. This system used closed-loop phase compensation and asymmetric H-T. Its output phase jitter was limited to ±0.5˚, and the optimal combing efficiency achieved 95.7%,

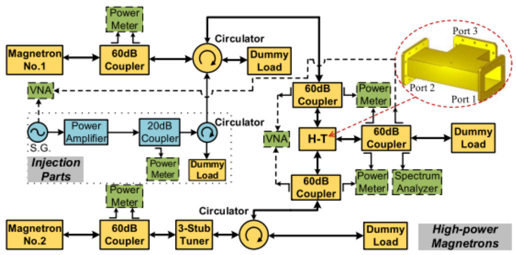


Fig. 5. Diagram of the phase-shifterless magnetron power controlled combining system.[6]

IV. FOUR-WAY POWER-COMBINEING SYSTEMS

In 2016, based on the research and experiments on injection-locked magnetrons and two-way power combining systems mention in section II and III. A four-way microwave power combining system based on 20 kW S-band magnetrons is proposed [7]. Magnetrons are injection-locked by hybrid injection-locking. Fig. 6 shows the diagram of the power combining system. In the power combining experiments, the output power and the combining efficiency of the system exceeded 60.6 kW and 91.5%. The amplitude stability of the system was less than 0.1dB (peak to peak) and the phase stability was ±0.9˚(peak to peak). This system realized the highest CW power, best combining efficiencies and spur suppression performances ever reported for an S-band magnetron power combining system.

V. CONLUSIONS

This paper introduced the research and experiments that caried out in last few years. The performance of 20 kW injection-locked S-band magnetron was improved. A four-way 60 kW microwave power combining system was established and the efficiency reached 91.5%, which set a new performance record. Power combining technique is important in high-power microwave applications, the research will also focus on realizing a compact and low-cost high-power microwave system, in the future.

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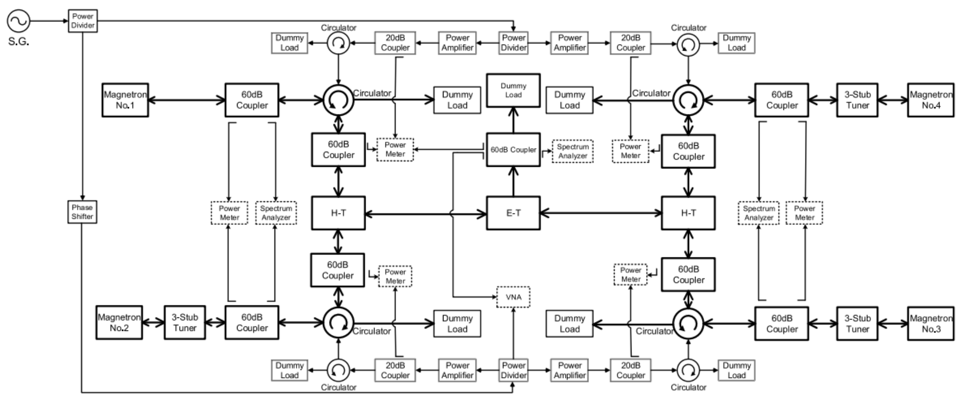

Fig. 6 Diagram of the 60-kW CW magnetron microwave power combining system. Dashed line framework part: measurement setup. Connected to signal generator (top and bottom) injection signal route. Highlighted middle part: high-power output route[7]

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