Experimental Study on the Phase Deviation of 20-kW *S*-Band CW Phase-Locked Magnetrons

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***Abstract*— Phase-control precision is important for applications of magnetrons in the microwave source array. Here, experimental results use a 20-kW *S*-band continuous-wave magnetron to investigate the phase deviation of large-power phase-locked magnetrons. For the first time, the phase deviation of a 20-kW magnetron controlled through an externally injected signal was studied. The phase deviation of the injection-locked magnetron output worsened gradually, the greater the difference in frequency of the injected signal (with the same injection ratio) from the center of magnetron injection-locked bandwidth was. When the injected power was maintained at 150 W and the magnetron output was at 19 kW, the maximum phase deviation was varied from approximately 1° to 6° with frequency tuning. In addition, the phase deviation of the phase-locked magnetron decreased as the injected signal power increased at a given frequency.**

***Index Terms*— Continuous-wave (CW) magnetron, injection-locked magnetron, phase comparison, phase deviation.**

I. Introduction

MAGNETRONS are widely used in military and industrial applications because of their high efficiency and low cost [1], [2]. Owing to increasing demands of greater power capacities in the important applications such as space solar power station, high-power transmitters, magnetrons have been studied to be applied in microwave source arrays [3],[4]. The phase-control precision of a magnetron's output microwave is very important for coherent power combining in microwave source arrays. However, the frequency characteristics of continuous-wave (CW) magnetrons are complex. It is difficult to achieve high efficiencies by directionally combining the output of multiple magnetrons. This disadvantage may be overcome by using phase-locked technology to stabilize the phase of magnetron's output.

Methods to injection-lock a magnetron include external injection-locking, peer-to-peer locking, and self-injected locking [5]–[7]. While the phase control of phase-locked CW magnetrons has been studied in various applications, details of the phase characteristics in the injection-locked magnetron experiments are less reported on. In 2004, Shinohara and Matsumoto [8] successfully developed a 300–500 W phase and amplitude controlled magnetron for microwave power transmission, and achieved a phase error of less than 1°. In 2006, Tahir *et al.* [9] successfully applied cooker magnetrons operated as a current-controlled oscillator through magnetron's pushing characteristic. In 2011, Dexter *et al.* [10] used a magnetron as an amplifier by utilizing phase control of a superconducting cavity for the first time. They achieved a phase noise of only 2° peak to peak (0.95 rms). Both of the above-mentioned phase-control methods control the magnetron's power supply to keep its microwave output stable. When a microwave external signal is injected into the magnetron, the phase difference between the magnetron and the injected signal is constant if the magnetron can be locked [6], [11]. Kazakevich *et al.* [12] has studied the phase–amplitude modulation of the CW magnetron and successfully accomplished phase control of the magnetron by injected microwave signals. In our previous experiments, we have observed the periodic behavior of the phase difference between the injection signal and magnetron output [13]. The report of phase-locked magnetron's phase deviation is rare. It is important to study magnetron injection-locked phenomena as these should be considered when phase-control magnetrons are applied for power combining with magnetron arrays.

This letter presents the phase deviation of an *S*-band large-power phase-locked magnetron into which an external microwave signal is injected. The "phase deviation" here means the fluctuation of phase difference between the injection signal and magnetron output (as shown in Fig. 2). The phase deviation of the phase-locked magnetron will vary with the frequency tuning or power tuning of the injected signal. In our experimental study, the phase deviation of two CW *S*-band phase-locked magnetrons investigated, specifically those of a large-power magnetron [13] and a Panasonic 2M210-M1 oven magnetrons. In large-power magnetron, the phase deviation of the phase-locked magnetron output is clearly visible, because the ripple of high dc power supplies is clearly observable.

II. Phase-Locked Magnetron Phase Experiments

Fig. 1 shows a diagram of the magnetron injection-locked measurement system. An *S*-band water-cooled CW industrial heating magnetron was used in the experiments. The magnetron's dc voltage was about −11.7 kV and supplied by a switched-mode power supply. The magnetic field intensity was 1550 Gs. The filament was supplied by the same switched-mode power supply as the magnetron. The anode current was 2.3 A, and the magnetron's output power is 19 kW.

Manuscript received February 5, 2018; revised March 21, 2018; accepted April 20, 2018. Date of publication May 24, 2018; date of current version June 5, 2018. This work was supported in part by the National Basic Research Program of China under Grant 2013CB328902, in part by the NSFC under Grant 61271074, and in part by the Fundamental Research Funds for the Central Universities, Southwest Minzu University, under Grant 2018NQN12. *(Corresponding author: Changjun Liu.)*

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Digital Object Identifier 10.1109/LMWC.2018.2832012

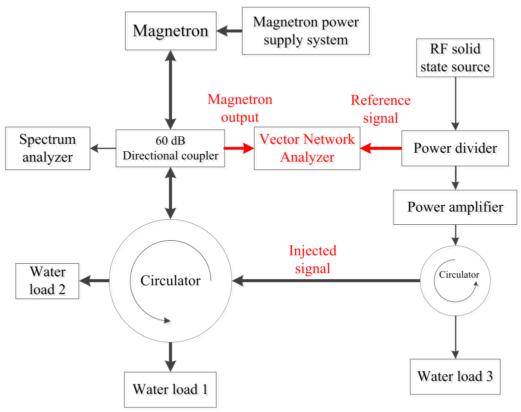

Fig. 1. Schematic of the magnetron's injection-locked measurement system.

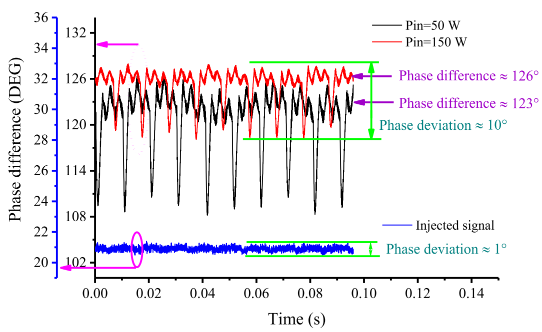

Fig. 2. Phase deviation of the injection-locked magnetron microwave output before the filament improvement. The injected signal is also shown.

To differentiate the phase of magnetron's output from that of the reference signal, the frequency spectra and phase conditions were measured [14]. The injected microwave signal was provided by a Hittite HMC-T2220 microwave source. Magnetron frequency-locking is a precondition of the phase comparison. The magnetron output microwave spectrum was monitored by a Rohde & Schwarz FSP spectrum analyzer. In the phase measurements, a power divider was applied to provide a stable reference signal. An Agilent E8363C PNA vector network analyzer was used to measure the phase difference between the reference signal and magnetron's output (red line in Fig. 1).

Because the phase of the reference signal was kept almost constant, we could use the phase comparison results to observe phase variations of the magnetron's output signal. The frequency of the vector network analyzer was set to be the same as that of the injected signal. The phase measurement results used the phase information of the trace b1/b2 of the vector network analyzer.

As shown in Fig. 2, the results of the phase comparison between the phase of the injected signal and that of the reference signal yielded a difference of less than 1. The phase deviation of the phase-locked magnetron output was about 15 when a 50 W signal was injected at a given frequency point.

When the input signal power was 150 W, phase comparison measurements showed the overall deviation range to be about 10°. When the power of the injection signal is increased, the comparison results show that the phase deviation is significantly reduced.

In Fig. 2, the main phase deviation is a periodic change of about 100 Hz, and this frequency is consistent with the ripple frequency of the filament current. It is thus reasonable to speculate that this 100 Hz periodic phase deviation is caused by the filament current. To remove this periodic wave, the filament's power supply is improved by reducing the power supply ripple.

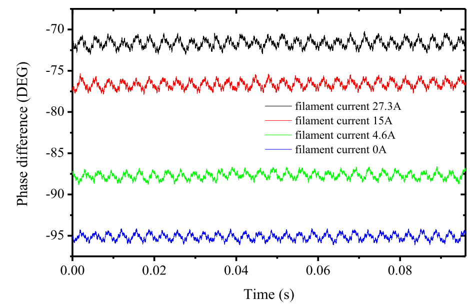

Fig. 3. Phase measurement with filament current tuning.

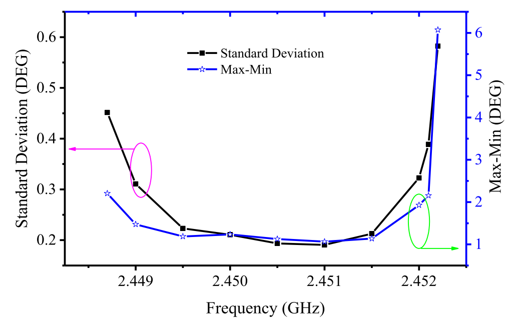

Fig. 4. Standard deviation and maximum peak-to-peak difference values as a function of the frequency of the injected signal.

After the filament current power supply improvement, the phase variation decreased significantly. To illustrate this, phase comparison results are shown in Fig. 3 for when a signal with the same injection power and frequency is injected into the magnetron and filament current is gradually tuned down. The noise of the filament current no longer has an impact on the phase deviation of the magnetron's output.

III. Phase Deviation of the Phase-Locked Magnetron

A. *Injected Signal Frequency Versus Phase Deviation*

When the phase deviation is small enough, even if the magnetron is locked at the edge of injection-locked bandwidth, the effect on the combining efficiency will be very small. At the edge of the magnetron injection-locked bandwidth, the magnetron spectrum observation shows good locking, but the phase deviation will vary with frequency tuning of the injected signal.

The phase deviation of the magnetron output is much greater when the frequency is close to the edge of the magnetron's injection-locked bandwidth. Here, the standard deviation is calculated from the measured phase. The maximum phase deviation (max–min) is the difference between the maximum and minimum values. The standard deviation of the magnetron phase comparison results for an injected power and magnetron output that were maintained at 150 W and 19 kW is shown in Fig. 4. The smallest phase deviation was 1.065° with injected signal frequency of 2.4510 GHz. When the injected signal frequency was at the edge of the injection-locked bandwidth, the maximum phase difference is about 6° and the overall standard deviation was less than 0.65°. Therefore, the

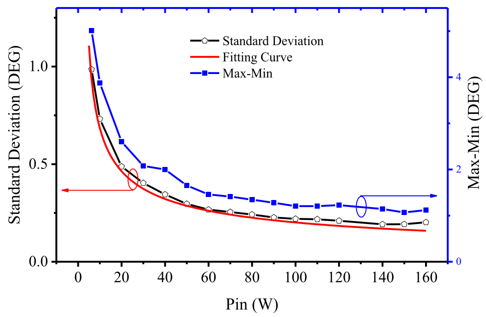

Fig. 5. Standard deviation and maximum peak-to-peak difference value as a function of the power of the injected signal.

effect of injection-locked magnetron (with the same injection ratio) was best in the center of the injection-locked bandwidth.

B. Injected Signal Power Versus Phase Deviation

When the power of the injected signals differs, the phase deviation differs. If the magnetron operation conditions are unchanged and the injected signal power is tuned, the results of the phase comparison of the magnetron output after the phase-locking is changed. The magnetron spectrum indicates good locking; however, the phase deviation decreased gradually as the injected signal power increased at a given frequency.

The standard deviation of the phase deviation was calculated according to the results of the phase comparison measurements, as shown in Fig. 5. When the injected signal power was increased from 20 to 150 W with the injected signal frequency 2.450 GHz, the phase deviation gradually decreased. When the power of the injected signal was increasing, the frequency spectrum of the magnetron was locked to one frequency, and the standard deviation and maximum peak-to-peak difference decreased.

As the injected power was increased, the phase deviation decreased. When the injected power was 20 W, the standard deviation of the magnetron phase deviation was less than 0.5 and the maximum phase deviation was only about 4. Before the improvement, when the input signal power was 150 W, the magnetron phase comparison displayed an overall deviation range of about 10° (in Fig. 2). The results show that a better phase stability is obtained with a smaller injection power after improvement.

The fitting curve is shown in Fig. 5 as well. The standard deviation of phase-locked magnetron's phase deviation θ_j is a function of the injected power. The fitting curve equation is

$$\frac{k}{\sin\theta_j} = \sqrt{\frac{P_{\text{in}}}{P_{\text{out}}}} \tag{1}$$

where $k = 0.0145$ in our experiments. Note that the injection ratio is the root of the ratio of the injected signal power and magnetron output power. Equation (1) is consistent with the solution of phase differential equation in the small injection ratio situation [15, eq. (6.3)].

IV. CONCLUSION

The phase deviation of a large-power phase-locked magnetron was investigated in *S*-band magnetron phase-locking experiments. For the first time, the phase deviation of a 20-kW *S*-band CW magnetron precisely controlled through an externally injected signal was studied. The phase deviation of the phase-locked magnetron decreased as the power of the injected signal was increased. Therefore, magnetron injection-locking is more difficult to accomplish under the same injection ratio when the frequency of injected signal is located away from the center of magnetron's injection-locked bandwidth. A better injection-locked output phase deviation is gained by our studies under the same injection ratio. The phase deviation of the magnetron will influence the combining efficiency in microwave power combining applications.

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