A Novel Anode Current Stabilization Method for Improving Magnetrons' Output Characteristic

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***Abstract* —An innovative anode current stabilization method is proposed to improve an S-band magnetron. The output characteristic of a magnetron with different anode current ripples is analyzed using theory and calculation. Then, a compact, low-cost current ripple eliminator is proposed, designed, and fabricated. In experiments, the injection-locked magnetron's anode current ripple is suppressed by 77.4%. Besides, its output phase jitter is reduced to 22.3% of the original, and its magnitude jitter is reduced from 0.49 dB to 0.09 dB when the injection ratio is 0.1. Furthermore, the output phase noise caused by the switch-mode power supply is mostly eliminated. The current ripple inhibition technique provides a novel idea to improve a magnetron's output characteristics at low cost, and it is expected to be used in applications that require high phase stability, such as phase-controlled arrays in wireless power transfer.**

***Keywords* —anode current ripple, injection-locked magnetron, magnitude stability, phase stability**

I. INTRODUCTION

Microwave applications have attracted more attention due to the development of microwave technologies [1][2]. Magnetrons are important microwave sources in applications such as wireless power transmission (WPT) and microwave heating because of their advantages of low cost, high power, and high efficiency [3]. However, free-running magnetrons also have defects of high phase noise and wide output spectrum, which restrict their use in applications requiring precise microwave output [4].

The injection-locking technique refers to injecting a high-stability external signal into a magnetron; when the power and frequency of the injected signal satisfy Adler's condition [5], the signal will lock the magnetron's output frequency. The injection-locking technique is a practical approach to realizing a magnetron's frequency and phase control. Injection-locked magnetrons have demonstrated their potential for high-precise microwave applications. T. Tahir et al. experimented with the characteristics of a magnetron injected and locked by an injected digital-modulated signal, and they showed that a magnetron is a candidate microwave source for microwave communication systems [6]. N. Shinohara et al. also carried out a series of experiments on simultaneous wireless information and power transfer (SWIPT) system; the performances of magnetrons injection-locked by different modulation signals are evaluated, and the first SWIPT system in the world based on injection-locked magnetron is proposed [7][8]. The injection-locked magnetron is also verified as the source of a super-conducting accelerating cavity. The research

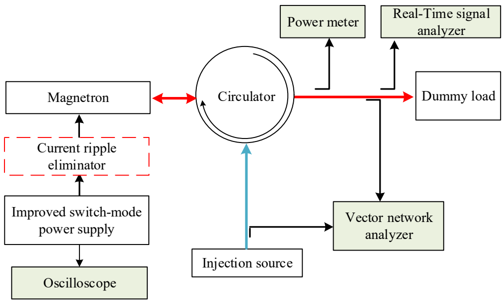

Fig. 1. The block diagram of the experiment injection-locked magnetron system

of M. Read [9] shows magnetrons' potential to drive a super-conducting accelerator.

The performance, including output phase stability and amplitude stability of an injection-locked magnetron, still suffers the influence caused by the distortion of its power supply's output. Researchers have reported different methods to improve the performance of an injection-locked magnetron. T. Mitani et al. successfully reduced the magnetron's output noise and realized a narrowband spectrum by cutting off the filament current [10]. I. Tahir et al. controlled the current of a switch-mode power supply to drive magnetrons in a phase-locked loop [11]. X. Chen reduced the phase noise and widened the locking bandwidth of an injection-locked magnetron by suppressing voltage ripple in a capacitor filter module [12] and then realized a solid-like injection-locked magnetron system by closed-loop phase compensation [13]. However, a phase-locked loop often increases the complexity and cost of the system, and a large-volume capacitor to eliminate the industrial frequency ripple is always bulky and expensive.

This work presents a novel approach to reduce the anode current ripple of the magnetron, enhancing its output phase and amplitude stability. The output characteristics of an injection-locked magnetron under different anode current levels are numerically analyzed. Additionally, a compact, low-cost, and simple current ripple eliminator (CRE) is implemented and tested to inhibit the current ripple. In the experiment (experiment system is shown in Fig. 1), a 1 kW S-band cook-type injection-locked magnetron's anode current ripple reduced from 31.4 mA to 7.1 mA. The peak-to-peak values of its output phase and amplitude jitters are suppressed from 2.51° to 0.56° and from 0.49 dB to 0.09 dB, respectively.

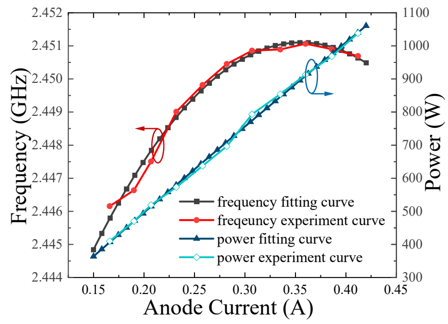

Fig. 2. Experiment and polynomial fitting curves of magnetron's power and frequency versus anode current

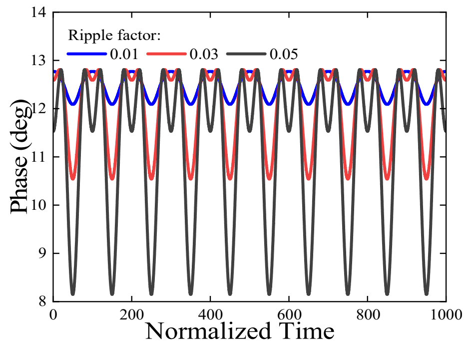

Fig. 3. Numerical analysis results of injection-locked magnetrons' output phase under different anode current ripple factors.

II. Effect of Anode Current Ripple on Magnetrons

A. Output Characteristics Effected by Anode Current Ripple

An injection-locked magnetron has a stable frequency as the injected signal. However, its output phase and amplitude are still influenced by various factors. The phase variation equation of an injection-locked magnetron is [4]:

$$\frac{d\theta}{dt} = \omega_{inj} - \omega_c - \frac{\omega_0}{2Q_{ext}}\rho\sin\theta \quad (1)$$

where ω_c is the free-running frequency of the magnetron, ω_{inj} is the frequency of the injected signal, $\theta=(\omega_{inj}-\omega'_c)t$ is the phase difference between the magnetron's output and injected signal, ω'_c is the output frequency of the magnetron under the influence of the injected signal, ω_0 is the resonant frequency of the magnetron's resonant cavity, Q_{ext} is the external quality factor of the magnetron, and $\rho=V_{inj}/V_{RF0}$ is the injection ratio. Frequency pushing effect illustrates that a magnetron's free-running frequency is related to its anode current I_{dc}, so in this case, we can rewrite (1) by the frequency and previously deduced output amplitude whose detail derivation isn't presented in this paper, then we obtain:

$$\frac{d\theta}{dt} = \omega_{inj} - \omega_c(\Delta I) - \frac{V_{inj}\omega_0}{V_{RF0}Q_{ext}}\sin\theta \quad (2)$$

$$\omega_c(\Delta I) \approx \omega_0 + \frac{b(I_0)}{2C} + \frac{\Delta I}{2C}\frac{\partial b(I_{dc})}{\partial I_0} \quad (3)$$

$$V_{RF0} = \frac{f(I_{dc})}{2RC\gamma},\ \gamma = \omega_0\left(\frac{1}{Q_0} + \frac{1}{2Q_{ext}}\right) \quad (4)$$

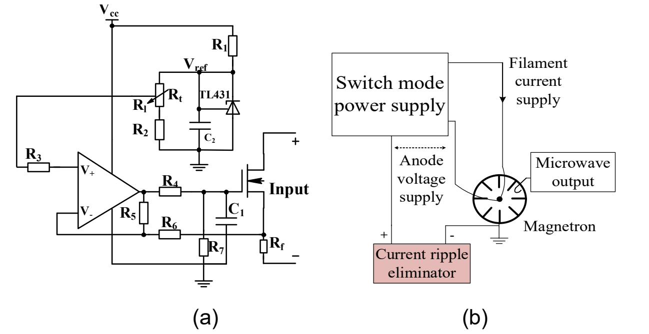

Fig. 4. (a) Diagram of the designed CRE. (b) Diagram of the power supply with the CRE.

where γ is defined as the growth parameter of the magnetron, *and R and C* in the diagram represent the equivalent resistance and capacitance of the magnetron resonant cavity, respectively. (2)-(4) shows that the injection-locked magnetron's output phase and amplitude are closely related to its anode current.

B. Numerical Analysis

To assist and verify the theoretical analysis, numerical analysis is carried out. The injection-locked magnetron's anode current I_{dc} can be described as $I_{dc}= I_0+\Delta I =I_0(1+S_r\cos(\omega_r t))$, where I_0 is the ideal anode current of a magnetron, ΔI is the ripple component, S_r is the ripple factor, and ω_r is the modulation frequency of the anode current ripple. Polynomial fitting methods are utilized in the calculation to simplify the derivation process. Fig. 2 gives out the frequency pushing curve of a Panasonic 2M210-M1 magnetron measured in experiments. Thus, the frequency and power of the magnetron is obtained as:

$$f_c(I_{dc}) = a_0 + a_1 I_{dc} + a_2 I_{dc}^2 \quad (5)$$

$$P_{RF0}(I_{dc}) = b_0 + b_1 I_{dc} + b_2 I_{dc}^2 \quad (6)$$

where a_0=2.4324 , a_1=0.1053, a_2=-0.1484, b_0=-41.9230, b_1=2748.9220, b_2=-294.9274. Then, the modulation frequency is set as 0.005, I_0 is 0.35 A, Q_{ext} is 400, and P_{inj} is 10 W. By substituting (5)(6) into (2), we use the four-order Runge-Kutta methods to solve the equation. Finally, the output function of a magnetron always is written as $V_{rf} = V_{RF0}\cdot\cos(\omega t+\theta)$. In this case, the output waveform of an injection-locked magnetron is obtained. Fig. 3 shows the calculated output phase of an injection-locked magnetron under different ripple factors. We know that the harmful modulation induced by the distortion of the anode current waveform deteriorates the output characteristic of the magnetron and reduces the current ripple, significantly improving the magnetron's stability.

III. Realization of Current Ripple Inhibition

A simple CRE is proposed to suppress the current ripple. MOSFETs are devices that can control current using the field effect. The voltage between the gate and the source controls the current flow through the drain to the source. Thus, a close-loop feedback circuit based on this characteristic will eliminate the current variation. The circuit schematic of the CRE is shown in Fig. 4 (a). A voltage regulator TL431

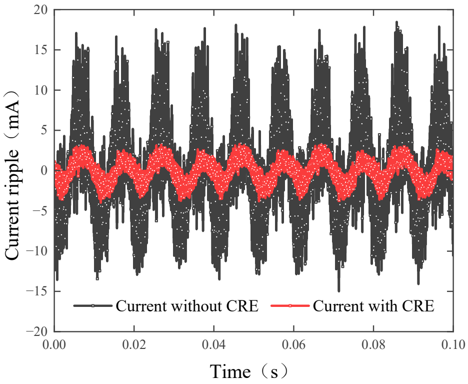

Fig. 5. Measured current ripples of the switch-mode power supply.

provides a 2.5 V reference voltage, and the R_t=5 kΩ will adjust the input voltage of the operational amplifier's non-inverting input. The MOSFET is IRFP460. The sample resistor R_f = 2.2 Ω is used to sample the current and provide a feedback voltage to the inverting input of the operational amplifier. We choose OPA690 as the operational amplifier, then we set the circuit parameters that C_1 = 22 μF, C_2=80 pF, R_f = 2.2 Ω, R_2 = R_t =2 kΩ, R_3 = R_4 = 1 kΩ, R_5 = 220 kΩ, R_6 = 47 kΩ and R_7= 4.7 kΩ to obtain the expected circuit function. Fig. 4 (b) gives the diagram of the improved power supply with the proposed CRE.

IV. Experiment Analysis and Discussion

A. Experiment Setup

The block diagram of the experimental injection-locked magnetron system is shown in Fig. 1. The magnetron is Panasonic 2M210-M1 (1 kW, 2.45 GHz), and it is powered by a switch-mode power supply (Welamp 2000f, Magmeet). A capacitor filter module pre-improved the power supply. The anode current ripple of the power supply is measured using a 1 Ω sample resistor and an oscilloscope (DPO-7254, Tektronix). The magnetron's output is detected by a Real-Time signal analyzer (RSA5126B, Tektronix), and the output power is measured by a power meter (AV2433). In the injection locking experiments, a signal generator (HMC-T2220, Hittite) and a high-gain power amplifier (ZHL-30W-262, Mini-Circuits) generate the injection signal. The phase and amplitude stability of the magnetron were measured using a vector network analyzer (Agilent N5230A). The dummy load is used to absorb the output microwave power.

B. Experiment Results and Discussion

The anode current ripples of the power supply are measured when the magnetron operating stably. The average value of the anode current is about 390 mA, and the anode voltage is maintained at 3.59 kV. Fig. 5 compares the anode current ripple of the magnetron under different conditions. We can observe that the peak-to-peak value of the power supply is 31.4 mA. The ripple frequency contains 100 Hz noise and ~50 kHz noise. When the CRE is connected to the system, the current ripple is reduced to 7.1 mA. The proposed CRE has a significant effect on current ripple suppression.

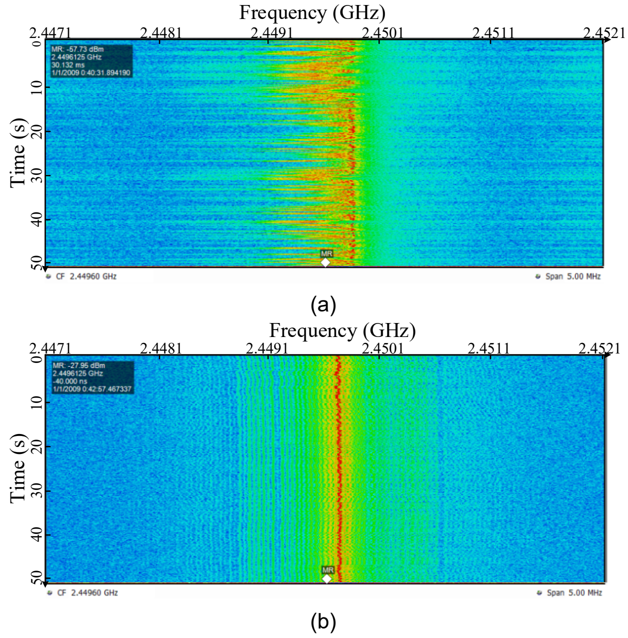

Fig. 6 Measured spectrograph of the free-running magnetron (a) without proposed CRE and (b) with proposed CRE on.

Then, we used the real-time signal analyzer to detect the spectrograph of the free-running magnetron. Fig. 6 shows the results. The color indicates the power level, and the x-axis and y-axis are frequency and time, respectively. These results show the proposed CRE significantly improves the output stability of the free-running magnetron. The range of the magnetron's frequency jitter (red region in Fig. 6) is reduced from about 760 kHz to 56 kHz. The output characteristics of the injection-locked magnetron are measured with an injection ratio of 0.1. Fig. 7 (a) shows the output spectrum. The output noise of the spectrum is eliminated greatly after the CRE is applied. The noise levels of the 50 kHz and 100 kHz noise caused by the high-frequency ripple of the power supply are reduced from -82.88 dB/Hz to -98.53 dB/Hz and from -85.80 dB/Hz to -95.52 dB/Hz, respectively. The measured output phase and magnitude jitters are shown in Fig. 7 (b) and (c). After the CRE is turned on, the peak-to-peak values of phase and magnitude jitters are suppressed from 2.51° and 0.49 dB to 0.56° and 0.09 dB. The 100 Hz ripple in the output phase and magnitude is almost completely eliminated. This result is consistent with the results of theoretical analysis and design.

Table 1 provides a comparison between the method proposed in this paper and other common methods. The current ripple inhibition method has a significant effect on enhancing the output performance of an injection-locked magnetron.

Naturally, this method also has the drawback of being applicable only when the ripple is within a specific range. It is prone to causing the breakdown of the MOS tube in the CRE when the value of the current ripple is too large. In this case, achieving ripple control may also potentially impact the operational state of the magnetron. Overall, the proposed CRE in this work still demonstrates good applicability and performance. It has the advantages of being low-cost and

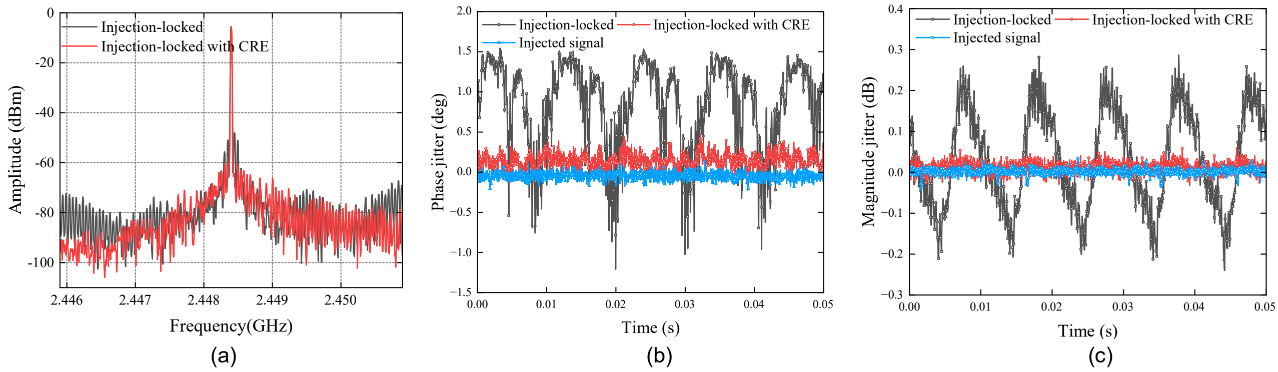

Fig. 7. Output characteristics of the injection-locked magnetron under different conditions. (a) Output spectrum. (b) Output phase jitter. (c) Output magnitude jitter.

Table 1. Comparison of our proposed method with other methods.

Method	Cost	Volume	Complexity	Phase jitter (Time)	Magnitude jitter (Time)	Injection ratio	Work
Anode voltage filter module	Medium	Large	Low	±0.9° (0.1s)	NM	0.105	[12]
PLL circuit	High	Medium	High	Almost ±0.5° (60s)	NM	0.13	[13]
				±0.8° (500ms)	NM	NM	[14]
Proposed CRE method	Low	Compact	Low	0.56° peak-to-peak (50ms)	0.09dB (50ms)	0.1	This work

*NM: not mention

compact and is expected to be partly instead of the large-volume, high-cost capacitors and inductors used for suppressing current ripple.

V. Conclusion

The output characteristic of a magnetron under the influence of anode current ripple is theoretically analyzed, and a novel method for performance improvement based on current ripple inhibition is proposed. The output stability of the magnetron is enhanced. After applying the proposed CRE, the anode current ripple is reduced from 31.4 mA to 7.1 mA, which significantly improves the output phase and magnitude stability of the magnetron. Additionally, the purity of the output spectrum is better than the original output. Our proposed method indicates a new approach to enhance the performance of an injection-locked magnetron. Due to its excellent effect on suppressing industrial frequency ripple, it is expected to partially replace large-volume and high-cost capacitors and inductors. In the future, this method is expected to be applied in various fields such as SWIPT, wireless power transmission, phased arrays, etc.

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