Performance Evaluation of a 20-kW Injection-locked Magnetron with Load-Pull Characterization

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2021 IEEE MTT-S International Wireless Symposium (IWS) | 978-1-6654-3527-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/IWS52775.2021.9499468

***Abstract*-A 20-kW S-band injection-locked magnetron with load-pull characterization system was actual test and verify. By searching the optimal load of the magnetrons, the performances of corresponding system could be improved. An enhanced injection-locked bandwidth, a low injection power and a preferable output phase noise performances were achieved. To the best of the authors' knowledge, this is one of the lowest injection power (3W) and highest phase noise performances (-85 dBc/Hz@50 kHz) ever reported for an S-band injection-locked magnetron with a power output of over 20 kW.**

Index Terms—Injection locking, magnetron, noise, bandwidth

I. Introduction

Simultaneous wireless information and power transfer, satellite communications and radar systems has been increasingly focused on high power and highly efficient oscillators, for example, the proposed Mars flight observation with a microwave power transfer (MPT) system required more than 10kW transmitting power [1]. Efficiency and cost are the primary consideration for such systems. Magnetrons, have been widely applied to household microwave ovens because of their low manufacturing costs and high energy efficiency. Meanwhile, the life time of magnetrons is relatively long as a result of the well-developed long-life cathode. Magnetrons seem an ideal candidate for such applications. However, the amplitude and phase of magnetrons fluctuate randomly, that is, magnetrons are noisy oscillators and magnetrons operates at multi-frequency mode, for example, 800-W microwave oven magnetrons generate spurious noise in whole frequency bands, and operate at 2450MHz with a frequency allowable error of 50 MHz.

To effectively solve the aforementioned frequency discrepancy and noise performance problem of magnetrons, injection locking is a well-known way to achieve stable frequency, amplitude and phase when the injection condition satisfies Adler's criterion. Shinohara [6] et al. achieved a phase-controlled magnetron at injection ratio of -30 dB, whose phase noise estimated to be less than -85 dBc/Hz at 10 kHz. Tahir [7] et al. developed a magnetron injection-locked by a phase modulated signal using frequency pushing technology, which delivered phase noise of -40 dBc/Hz@ 100 kHz. The current works mainly focus on the household magnetrons whose output power are less than 1 kW, such output power of a magnetron cannot meet the rapidly increasing requirements of aforementioned applications, and obviously the higher the magnetron's output power is, the poorer performance we suffer. Though the idea of injection locking is fascinating, still highly stable and pure output of magnetrons by this method is not easily achieved. Thus, it is attractive to explore enhanced methods for improving the injection ratio, locking bandwidth and output spectral purity of an injection-locked magnetron.

This paper presents a performance evaluation of a 20-kW injection-locked magnetron with load-pull characterization, and no such studies have been conducted to date. Experiments of this system has been carried out, and the measured results are in accord with the theoretical predictions

II. Experiment system

The block diagram of a 20 kW continuous wave (CW) injection-locking magnetron using load pull based on WR430 waveguides is shown in Fig. 1.

The water-cooled 20-kW CW magnetrons(CK-2091) used for the experiments were manufactured by Nanjing Sanle Electronic Information Industry Group Co., LTD, China. The magnetic field was supplied by an extra electromagnet, whose operating DC current and magnetic intensity were 3.2 A and 1250 Gs, respectively. A DC switching power supply with a voltage ripple of less than 1.5% was applied to supply the anode voltage and current. The initial preheating cathode current is 47.0 A, and when the output power of free-running magnetrons reached 15.0 kW, that current was decreased to approximately 25.0 A to reduce the frequency modulation noise, and help expand the longevity of the CW magnetrons.

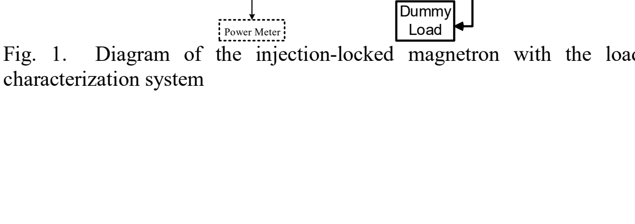

Fig. 1. Diagram of the injection-locked magnetron with the load-pull characterization system

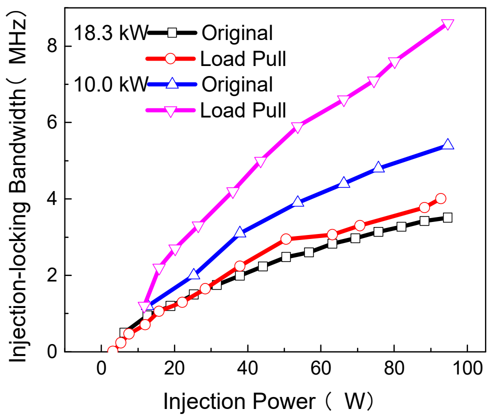

Fig. 3. The injection locked bandwidth with various injection ratios at different state.

The injection signals, provided by a signal generator (E8267C, Agilent) amplified with a 40 dB power amplifier (YYPA4D, Sanle Microwave Co., Nanjing, China), was transmitted to the magnetron by a circulator (26WHPDPSC 30 kW, HD Microwave Co., Xi'an, China) with the dummy loads (KT-22WWL30kW, KT Microwave Co., Nanjing, China). Additionally, the load pull of the magnetron was realized by a 3-stub tuner (HD-22WST3, HD Microwave Co., Xi'an, China). By tuning 3-stub tuner, the desired magnetron impedance was obtained. The performance of a 20-kW injection-locked magnetron was evaluated between two states.

A 60-dB directional coupler (LOOP22DC60D20C1010N, Euler) was employed to sample the magnetron outputs for the power (power meter, AV2433, the 41st Institute of CETC), the spectrum and phase noise measurements (signal analyzer, FSV40, Rohde & Schwarz). A 20-dB directional coupler (SLDC-20-7F-NF, Rosenberger Co., Germany) was employed to sample injection signals for power measurements (power meter, AV2433, the 41st Institute of CETC).

III. Results and Discussion

Based on the single-mode equivalent parallel RLC resonance circuit of the magnetron oscillator, the instantaneous phase between an injection-locked magnetron output and injection signal (the injection signal should be weak) is represented by [8]

$$\frac{d\theta}{dt} = \omega_0 \frac{\rho}{2Q_e} \sin\theta + \omega_f - \omega_{inj} \qquad (1)$$

where $\rho = \sqrt{P_{inj}/P_{out}}$ is the injection ratio, $\omega_0 = \sqrt{LC}$ is the resonance frequency, Qe is the external quality factor of the magnetron and ωf is the instantaneous angular frequency of the magnetron. $\theta = (\omega_f - \omega_{inj})t + \varphi$, φ is the phase difference between the reference signal and the output of the free-running magnetron, and t is the time.

Thus, if the magnetron is injection-locked, the phase difference becomes constant, we could get the injection locking well-known Adler's condition from (1)[9]:

$$\frac{\rho\omega_0}{2Q_e} \geq \left|\omega_f - \omega_{inj}\right| \qquad (2)$$

Apparently, equation (2) illustrates that when the injection power is constant, the locking bandwidth can be extended substantially by decreasing the external Qe factor through tuning the magnetron's load. Similarly, when the frequency difference of magnetron output and injection signal is constant, the corresponding injection-locked magnetron can achieve relatively low injection power by decreasing the Qe factor of the injection locked magnetron by the same way.

To illustrated the abovementioned, the magnetron anode voltage and current was set to −11.89 kV and 2.10 A, which results in an output power of 18.3 kW and operating frequency of 2447.5 MHz. As shown in Fig.3, choosing the original state (Qe=102) and a low Qe state (Qe=88), the injection-locked perfomance was measured when the various injection power was injected for comparison. When the Qe factor was tuned to 88, it was the first time that the 20-kW magnetron had been locked at an injected power of 3W. Moreover, when the injection power was increased, the injection bandwidth was extended as well. When the fixed injected power was 100 W, the injection-locked bandwidth was 3.9 MHz at the low Qe state, and an original injection-locked bandwidth was 3.4 MHz. The bandwidth increased 0.4 MHz by tuning the magnetron load. To obtain a obvious and easy proof for this conclusion, the magnetrons was set to operate at 2446 MHz with an output power of 11.2 kW (magnetron anode voltage of −11.89 kV and anode current of 1.40 A), when the injection power was 100 W, the magnetron under the same load-pull characterization supplied nearly 1.6 times locking bandwidth of an original injection-locked magnetron.

On the other hand, the spectral density of phase noise for an injection-locked magnetron can be represented as following Pengvanich's method [10]:

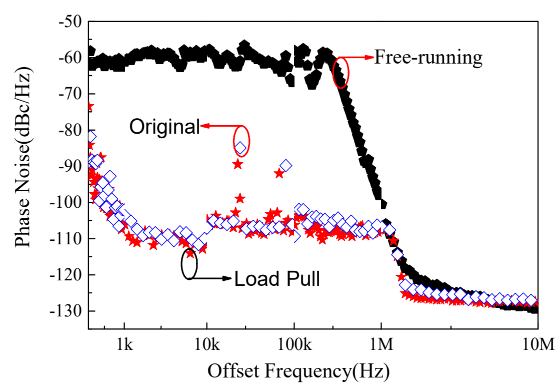

Fig. 4. The phase noise of the magnetron.

$$\left|\delta\tilde{\theta}(\omega)\right|^2=\frac{\left|\delta\tilde{\omega}_f(\omega)\right|^2}{\omega^2+\left(\frac{\rho}{2Q_e}\right)^2-\left(\frac{\omega_f-\omega_0}{\omega_0}\right)^2} \quad (3)$$

where δθ(ω) is the spectral density of phase noise, δωf(ω) is the fluctuation in the free-running frequency.

Then equation (3) illustrates that when others are constant, the phase noise are improved by decreasing the external Qe factor through tuning the magnetron's load.

Fig. 4 shows the phase noise of the magnetron's output characteristics at two different states. Fig. 4 shows that the phase noise of the free-running magnetron is poor, and the frequency fluctuated randomly during the free-running operation. Also, the free-running frequency may shift with respect to time. The output phase noise improved visibly and was measured to be −78 dBc/Hz@50 kHz, when the magnetron was injection locking, Considering the load-pull characterization, the phase noise could increase to -85 dBc/Hz@50 kHz, which is a significant improvement compared with an original injection-locked magnetron, the phase noise that deteriorated at 50 kHz was caused by the ripple of the DC switching power supply.

Additionally, to the best of the authors' knowledge, this is one of the lowest injection power (3W) and highest phase noise performances (-85 dBc/Hz@50 kHz) ever reported for an S-band injection-locked magnetron with a power output of over 20 kW.

IV. Conclution

A 20 kW S-band injection-locked magnetron with load-pull characterization system was actual test and verify. By searching the optimal load-pull characterization, performances of the corresponding system could be improved. An enhanced injection-locked bandwidth, a low injection power and a preferable output phase noise performances were achieved. To the best of the authors' knowledge, this is one of the lowest injection power (3W) and highest phase noise performances (-85 dBc/Hz@50 kHz) ever reported for an S-band injection-locked magnetron with a power output of over 20 kW. The improved 20-kW injection-locked magnetron has more attractive to be applied as a cost-effective and high-power microwave source for simultaneous wireless information and power transfer system, radar, and modern communications.

Acknowledgment

This work was supported in part by the *973* program *2013CB328902*, and fund of No.*10* Research Institute of China Electronics Technology Group Corporation

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