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Theoretical and experimental study on frequency pushing effect of magnetron*

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The applications of magnetrons are greatly limited because of the poor output spectrum of the free-running magnetron. Currently, one of the best ways to solve this problem is injection locking. However, the injection locking theory which is widely used nowadays is based on the simplified oscillator, which does not include the frequency pushing effect of the magnetron. In this paper, the theory of injection locking magnetrons with frequency pushing effect is systematically studied. Analytical analysis shows that the locking bandwidth turns larger with the consideration of the pushing parameter (α), and the increase of locking bandwidth is expanded with α increasing. Experimental results show that the locking bandwidth is expanded by 0.3 MHz, 1 MHz, and 1.6 MHz compared with the locking bandwidth from the conventional locking theory under an injection ratio (ρ) of 0.05, 0.075, and 0.1, respectively. This research provides a more accurate prediction of the properties of the injection-locked magnetron.

Keywords: magnetron, injection locking, pushing effect

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1. Introduction

Magnetrons have been widely used in industrial microwave heating, healthcare, food defrosting, microwave plasma, *etc*.[1–5] due to its low cost, high output power, high efficiency, and small size[6,7] Nowadays, magnetrons are further applied to diamond deposition and composite materials preparation, the power synthesis, communication, *etc*., which require higher frequency and power stability.[8–11] However, the free-running magnetrons have problems of unstable frequency stability, poor consistency, and wideband output spectrum.[12,13] Currently, injection locking of magnetron is the most widely used method to solve these problems.[14]

The widely used theoretical guideline of the injection locking magnetron is the Adler's condition,[15,16] as shown in the following equation:

$$\frac{\rho}{Q_{\text{ext}}} \geq \frac{\omega' - \omega}{\omega_0}, \tag{1}$$

which is established based on the simplified parallel resonant circuit without considering the nonlinear frequency pushing effect of the magnetron.[17] The frequency pushing effect causes that the locking bandwidth, the output frequency, and power of the injection locking magnetron to slightly differ from the prediction calculated by the traditional Adler's condition, which makes it unable to meet the requirements for diamond deposition and composite material preparation, power synthesis, communication, *etc*. Under this circumstance, the frequency pushing effect on injection locking magnetron must be considered. The effect of frequency pushing has been studies preliminarily, and the corresponding equations are deduced. However, the equations have the problem of multiple solutions, which leads to the discrepancy between the experimental observation and the theoretical prediction in frequency and power.[18]

In this paper, based on the equivalent circuit model of magnetron with frequency pushing effect, the relationships between the radio frequency (RF) amplitude and locked frequency under different frequency pushing parameters (α) and injection ratios (ρ) are given in detail. Analytical analysis shows that both the locking bandwidth and the increment of locking bandwidth are expanded with α increasing when ρ is constant. When α is constant, the locking bandwidth also increases as ρ increases. In addition, the amplitude of output power also varies with the injection frequency. In the traditional theory, when the injection frequency is the same as the free-running frequency, the magnetron has the maximum output power. But after considering the frequency pushing effect, the maximum output power occurs when the injection frequency is slightly lower than the free-running frequency. Based on the theoretical analysis, we carry out the injection locking experiments by utilizing continuous magnetron (Panasonic 2M244-M1). The experimental results show that the locking bandwidth of the magnetron is 6%, 14%, and 17% wider than that calculated under the Adler's condition, and the

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injection frequency at which the maximum RF output power is recorded is 1 MHz, 2 MHz, and 3 MHz lower than the free-running frequency under an injection ratio of 0.05, 0.075, and 0.1, respectively.

2. Theoretical analysis

The magnetron is a kind of oscillator, whose equivalent circuit can be represented in Fig. 1. The resonant cavity of magnetron can be equivalent to an *RLC* parallel resonant circuit. The mechanism of electron interaction in the magnetron cavity can be represented by electronic admittance $g+\mathrm{j}b$. The $G+\mathrm{j}B$ represents the load with nonlinear complex admittance.[18]

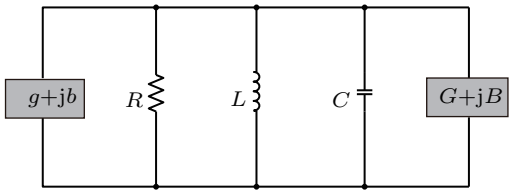


Fig. 1. Magnetron equivalent circuit model.

On the other hand, magnetrons are also categorized as vacuum tubes, which has complex nonlinear frequency pushing effect. In the equivalent circuit, nonlinear characteristics can be represented by g and b which are expressed according to the frequency pushing parameters α[19]

$$g = \frac{1}{R}\left(\frac{V_{\mathrm{dc}}}{V_{\mathrm{RF}}} - 1\right), \tag{2}$$

$$b = b_0 - g \cdot \tan\alpha, \tag{3}$$

where V_{dc} is the dc voltage, V_{RF} is the RF amplitude of the magnetron, and b_0 is a constant.

For the injection-locked magnetron, the RF amplitude and the phase characteristics can be expressed by[18]

$$V_{\mathrm{RF}} = \frac{V_{\mathrm{RF0}}}{1 + \dfrac{\rho\cos\theta}{\dfrac{Q_{\mathrm{ext}}}{2}\left(\dfrac{1}{Q_{\mathrm{L}}} + \dfrac{1}{RC\omega_0}\right)}}, \tag{4}$$

$$\frac{1}{\omega_0}\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{\rho}{Q_{\mathrm{ext}}|\cos\alpha|}\sin(\theta-\alpha) + \frac{\omega'-\omega}{\omega_0}, \tag{5}$$

where V_{RF} is the RF amplitude of locked magnetron. V_{RF0} is the RF amplitude of free-running magnetron, θ represents the phase difference between the injection signal and magnetron's output signal, ω is the output frequency, which is equal to the injection signal frequency when magnetron is locked, ω' is the free-running frequency, ω_0 is the resonance frequency of the magnetron cavity, Q_{L} is the loaded quality factor and Q_{ext} is an external quality factor.

The phase difference θ is constant when the magnetron is fully locked, which indicates that $\mathrm{d}\theta/\mathrm{d}t$ in Eq. (5) equals zero after injection-locking. Therefore, θ can be solved as follows:[18]

$$\theta = \arcsin\left(\frac{\omega'-\omega}{\omega_0}\frac{Q_{\mathrm{ext}}|\cos\alpha|}{\rho}\right) + \alpha. \tag{6}$$

Inserting Eq. (6) into Eq. (3), the RF amplitude can be obtained as follows:

$$V_{\mathrm{RF}} = \frac{V_{\mathrm{RF0}}}{1 + \dfrac{2\rho}{\omega_0 Q_{\mathrm{ext}}\left(\dfrac{1}{Q_{\mathrm{L}}} + \dfrac{1}{RC\omega_0}\right)}\cos\left(\arcsin\left(\dfrac{\omega'-\omega}{\omega_0}\dfrac{Q_{\mathrm{ext}}|\cos\alpha|}{\rho}\right) + \alpha\right)}. \tag{7}$$

Equation (7) reveals the correlation between the RF amplitude and the frequency of the injection locked magnetron. According to Eq. (7), we carry out the analytical analysis to further demonstrate the relationship between the locked frequency and RF amplitude under different values of injection ratio (ρ) and different values of pushing parameter (α) as shown in in Fig. 2.

From Fig. 2(a), when α is constant (taking $\alpha = 0.6$ for example), with the increase of ρ, the locking bandwidth of the injection locked magnetron increases. Moreover, the locking bandwidth is wider than that predicted under the conventional Adler's condition, which is shown in the range bounded by dashed lines in Fig. 2(a). Simultaneously, the increment of locking bandwidth increases with the increase of ρ.

On the other hand, the RF amplitude also varies with the injection frequency. It can be found that the RF amplitude of the locked magnetron is asymmetric with respect to the center line which corresponds to the frequency of free-running magnetron. As the injection frequency moves away from the frequency of free-running magnetron, the RF amplitude of the lower injection frequency is higher than that of the higher injection frequency. One thing should be noticed is that the variation trends of the theoretical curve conflicts with the scenario in Fig. 4 in Ref. [18], which is because we calculate first the phase difference, and then the amplitude of the output signal with the calculated phase difference, while in Ref. [18], the author drew the figure with the other solution of the quadratic equation (30) in Ref. [18].

In Fig. 2(b), when maintaining ρ, the locking bandwidth of the magnetron increases with the increase of α. Simulta-

neously, the maximum RF amplitude remains fixed under the same ρ, but the position of the maximum RF amplitude shifts toward lower frequency with α increasing. This discovery will better guide the applications of injection locked magnetrons.

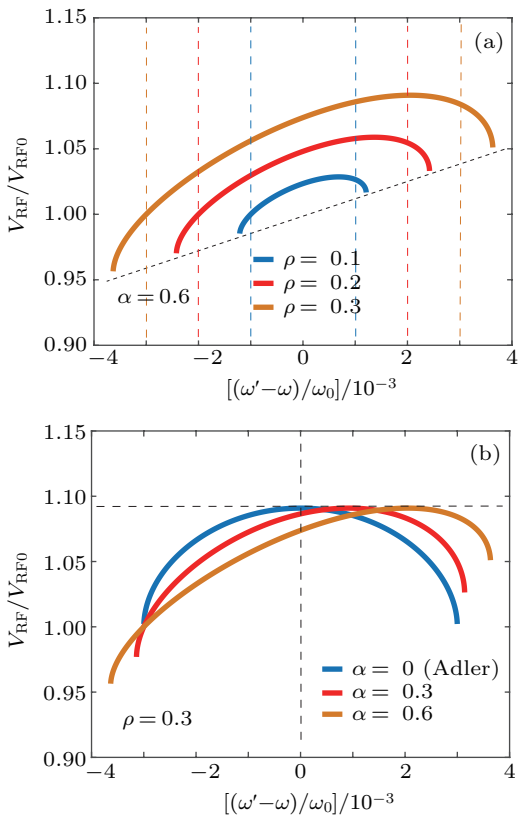


Fig. 2. Relationship between locked frequency and RF amplitude for (a) different values of ρ under constant α and (b) different values of α under constant ρ.

3. Experimental setup

The theoretical analysis shows that when the frequency pushing effect is taken into account, the locking bandwidth of the magnetron will be wider than that calculated under the Adler's condition, and the variation trend of output power amplitude also changes. In order to verify the correctness of the theory, we carried out experiments by using continuous magnetron (Panasonic 2M244-M1). The schematic diagram of the experimental system is shown in Fig. 3. The magnetron generated approximately 1-kW microwave power, which was absorbed by the water load 1, which has some advantages: high-power capacity, small size, light weight and very nice heat dissipation properties compared with dry loads. In this process, the output spectrum and output power of the magnetron were coupled by a double directive coupler and measured with the spectrum analyzer (R&S FSP7) and power meter (AV2433). respectively.

The injected signal was generated by the Agilent E8267C signal generator and amplified by a power amplifier. The injection signal was injected into the magnetron through circulators. The frequency of the injection signal was adjusted in steps of 1 MHz. Two cascaded circulators were used to separate the injection signal from the reflected power of the magnetron. The separated reflected power is absorbed by water load 2.

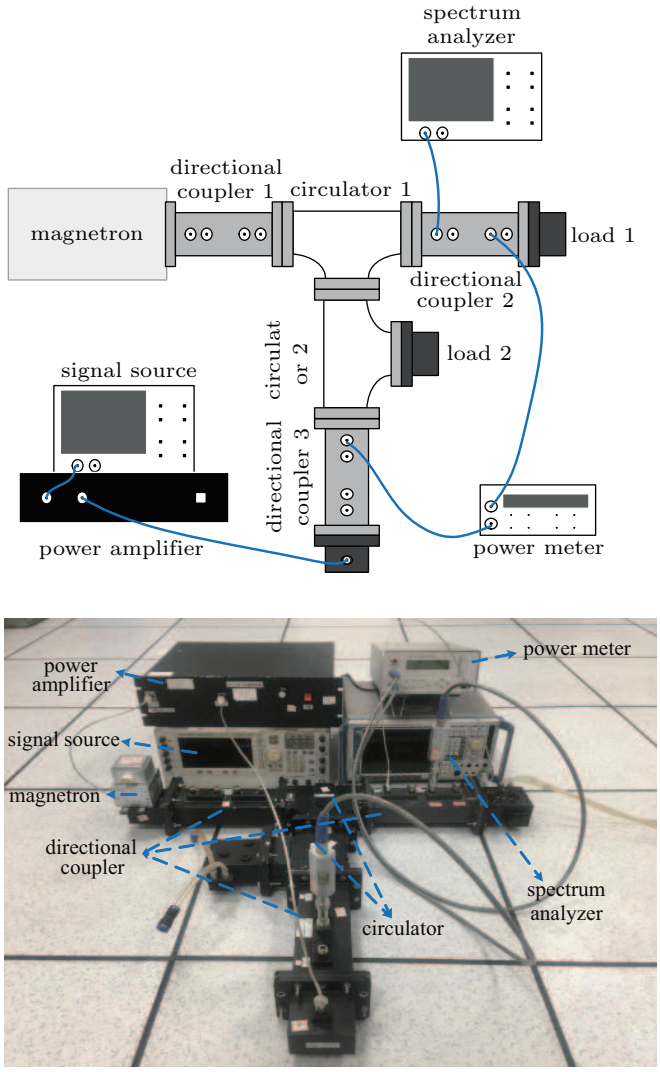


Fig. 3. Schematic diagram and photograph of the measuring setup.

4. Results and discussion

In the experiments, on the premise that the magnetron is locked, the output power of the locked magnetron is measured at different injection frequencies under different injection ratios. The experimental and theoretical results are compared in Fig. 4 and Table 1. The theoretical curves are obtained by fitting the experimental data to obtain an appropriate value of the frequency pushing parameter α. The experimental data under different injection power are obtained with the same magnetron, Therefore, in Fig. 4, curve fitting is carried out with the same α under different injection ratios, and α of this magnetron should be 0.5.

As shown in Fig. 4, the experimental results are consistent with the theoretical curves under different injection power.

Just like the previous analytical analysis results, as the injection frequency sweeps from high to low, the output power increases first and decreases then. The maximum output power values are consistent with the theoretical results. The maximum output RF power occurs at the frequency lower than the free-running frequency. In addition, the range bounded by two vertical purple lines represents the locked bandwidth calculated under the Adler's condition. Both experimental results and theoretical curves show that the locking bandwidth is wider than that under the Adler's condition for different injection power. The comparison is demonstrated in detail in Table 1.

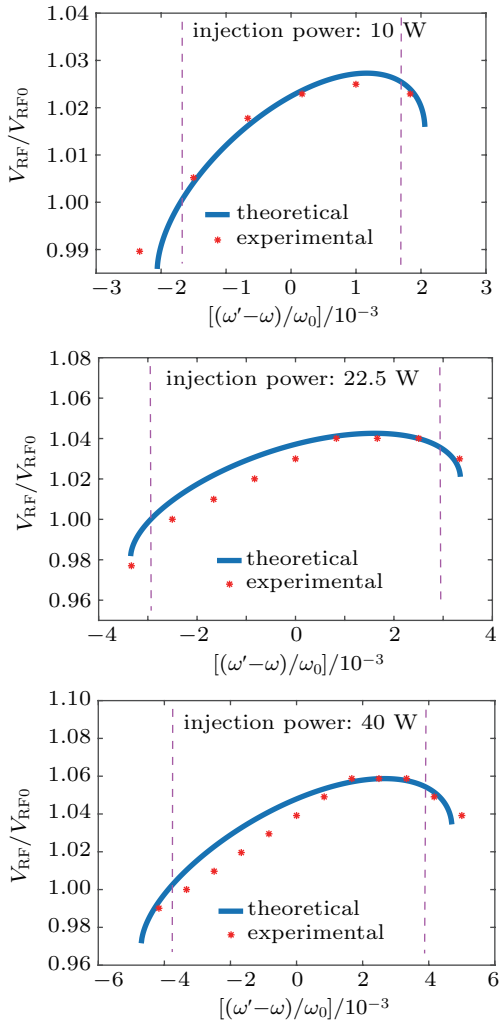


Fig. 4. Comparison between the theoretical and experimental results under injection power of (a) 10 W, (b) 22.5 W, and (c) 40 W, with range bounded by two vertical purple dashed lines representing locked bandwidth calculated under the Adler's condition.

Table 1. Comparison of injection locking bandwidths under different injection power.

Locking bandwidth* \ Injection power	10 W	22.5 W	40 W
Adler	4.7	7.05	9.4
Pushing effect	5.4	8.04	10.72
Experimental	5	8	11

*Locked bandwidth is in MHz.

The injection power values used in the experiments are 10 W, 22.5 W, and 40 W respectively, the corresponding injection ratios are 0.05, 0.075, and 0.1 respectively. The locked bandwidths calculated under the Adler's condition are 4.7 MHz, 7.05 MHz, and 9.4 MHz respectively. The locking bandwidths obtained in our experiments are 5 MHz, 8 MHz, and 11 MHz respectively which are 0.3 MHz, 0.95 MHz, and 1.6 MHz larger than those calculated under the Adler's condition. The theoretical locking bandwidths considering the frequency pushing effect ($\alpha = 0.5$) are 5.4 MHz, 8.04 MHz, and 10.72 MHz respectively, which are very close to the experimental results.

5. Conclusions

The magnetron has complex nonlinear frequency pushing effect, which has a great influence on the injection locking process of the magnetron. If the nonlinear frequency pushing effect of magnetron is not considered, the prediction of magnetron output is inaccurate, which may seriously affect the applications of magnetron in diamond deposition and composite materials preparation, power synthesis, communication, *etc*. In this paper, the frequency pushing effect of the injection-locked magnetron is studied theoretically and verified experimentally. Theoretical analysis show that the existence of frequency pushing effect leads the locking bandwidth of the magnetron to be wider than that predicted under the Alder's condition. What is more, the increment of the locking bandwidth is also closely related to the frequency pushing parameter α. Simultaneously, the output power of the locked magnetron also varies with injection frequency. The output power of the magnetron reaches a maximum value as the injection frequency is lower than the free-running frequency. That is to say, the maximum output power appears at the position where $(\omega' - \omega)/\omega_0$ is greater than zero. The frequency gap turns wider as pushing parameter α increases. The validity of these theory is also demonstrated experimentally. The research results help people to have a more in-depth understanding of the magnetron injection locking process. The theoretical formula can be used to predict the magnetron locking state more accurately. Supported by the above researches, the injection-locked magnetrons will play a more important role in implementing power synthesis, communications and other relevant applications.

References

[1] Stuchly M A and Stuchly S S 1983 *IEE Proc. A* **130** 467
[2] Zhang Y, Agrawal D K, Cheng J and Tania Slaweck 2018 *IEEE Trans. Microw. Theory Tech.* **66** 2107
[3] Osepchuk J M 1984 *IEEE Trans. Micrrow. Theory Techn.* **32** 1200
[4] Kamo M, Sato Y, Matsumoto S and Setaka N 1983 *J. Cryst. Growth* **62** 642

[5] KaKati H and Borah S M 2015 *Chin. Phys. B* **24** 125201
[6] Zhang Y, Huang K, Agrawal D K, Tania Slawecki, Huacheng Zhu and Yang Yang 2017 *IEEE Trans. Electron. Dev.* **64** 4272
[7] Yuan P, Zhang Y, Ye W, Zhu H, Huang K and Yang Y 2016 *Chin. Phys. B* **25** 078402
[8] Brewer M A, Brown I G, Dickinson M R, Galvin J E, MacGill R A and Salvadori M C 1992 *Rev. Sci. Instrum.* **63** 3389
[9] Yan J, Wei T, Qiao W, Shao B, Zhao Q, Zhang L and Fan Z 2010 *Electrochim. Acta* **55** 6973
[10] Small J G (U.S. Patent) 7 257 327 [2007-8-14]
[11] Ye W J, Zhang Y, Yuan P, Zhu H C, Huang K M and Yang Y 2016 *Chin. Phys. B* **25** 128402
[12] Zhang Y, Yuan P, Ye W, Zhu H, Yang Y and Huang K 2016 *Int. J. Appl. Electromagn. Mech.* **51** 71
[13] Yue S, Gao D P, Zhang Z C and Wang W L 2016 *Chin. Phys. B* **25** 118403
[14] Zhang Y, Ye W J, Yuan P, Zhu H C, Yang Y and Huang K M 2016 *Chin. Phys. B* **25** 048402
[15] Adler R 1946 *Proc. IRE* **34** 351
[16] Pengvanich P, Neculaes V B, Lau Y Y, Gilgenbach R M, Jones M C, White W M and Kowalczyk R D 2005 *J. Appl. Phys.* **98** 114903
[17] Welch H W 1953 *Proc. IRE* **41** 1631
[18] Chen S C 1990 *IEEE Trans. Plasma Sci.* **18** 570
[19] Slater J C 1947 *Tech. Rep.* **35** 1