Power-combining based on master–slave injection-locking magnetron*

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A microwave power-combining system composed of two Panasonic 2M244-M1 magnetrons based on master–slave injection-locking is demonstrated in this paper. The principle of master–slave injection-locking and the locking condition are theoretical analyzed. Experimental results are consistent with the theoretical analysis and the experimental combined efficiency is higher than 96%. Compared with the external-injection-locked system, the power-combining based on the master–slave injection-locking magnetron is superior by taking out the external solid-state driver and the real-time phase control system. Thus, this power-combining system has great potential for obtaining a high efficiency, high stability, low cost, and high power microwave source.

Keywords: magnetron, power-combining, master–slave injection-locking, combined efficiency

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1. Introduction

High power microwave source is urgently needed in a variety of areas such as environmental engineering,[1,2] nanostructures pyrolysis,[3] plasma heating,[4,5] and material processing.[6,7] In particular, the solar power satellite (SPS) is hotly discussed as a result of transferring solar energy to Earth using microwaves.[8] Magnetron whose efficiency routinely exceeds 80% and unit cost less than 7 $ is very suitable for these applications.[9,10] However, magnetron has some drawbacks such as the power capacity limit for one magnetron, wide-band output, unstable frequency and uncontrolled phase which make it difficult to directly apply in large-scale industrial applications.[11] To solve these problems, an alternative way is power-combining. Dutch physicist Christiaan Huygens observed the synchronization behavior of two closely hung pendulum wall clocks in 1665 which inspired people to study locking phenomena,[12] Adler found the locking condition of phase locking oscillators in 1940s.[13] Benford and Woo used a short waveguide to connect two magnetrons and obtained phase locking in their peer-to-peer locking system in 1988.[14] Peer-to-peer phase locking of magnetrons provides a new method which uses the coupling between the magnetrons instead of external signals. However, a large amount of couplings are required in a multiple-magnetron system with the peer-to-peer locking method, so the system is difficult to be applied for large-scale power combining.[15] Power combining based on the external-injection-locked magnetron has been proposed. The system is very complex and expensive because every magnetron needs an external solid-state driver and a central control system should be provided to adjust the phase difference of the magnetrons.

In this work, we propose a power-combining system based on the master–slave injection-locking magnetron. Compared with the previous systems, this system does not need an external solid-state driver or a real-time phase adjustment system, and the combined efficiency reaches as higher as 96%. This method provides a solution for a high power, low cost microwave source.

2. Theory analysis

Figure 1 shows a circuit model of a locked magnetron in which the free-running state is represented by an *RLC* circuit and the master injection power is represented by current I.[16,17] From the Kirchhoff voltage law, we can obtain

$$\frac{V}{R}+\frac{V}{\mathrm{j}\omega L}+\mathrm{j}\omega CV+YV=-I. \tag{1}$$

In the above equation, admittance Y represents the nonlinear beam-loaded which can bring a Q in a hot test as well as ω and the voltage of amplitude V_1. Using $\omega=\sqrt{1/LC}$ and $Q=\omega RC$ to simplify Eq. (1) of time-domain, we have

$$\frac{\mathrm{d}^2V}{\mathrm{d}t^2}+\frac{\omega}{Q}\left(1-\frac{V}{V_1}\right)\frac{\mathrm{d}V}{\mathrm{d}t}+\omega^2V=-\frac{1}{C}\frac{\mathrm{d}I}{\mathrm{d}t}. \tag{2}$$

When magnetrons 1 and 2 are coupled, the system is expressed as

$$\begin{bmatrix}I_1\\I_2\end{bmatrix}=\begin{bmatrix}Y_{11}&Y_{12}\\Y_{21}&Y_{22}\end{bmatrix}\begin{bmatrix}V_1\\V_2\end{bmatrix}. \tag{3}$$

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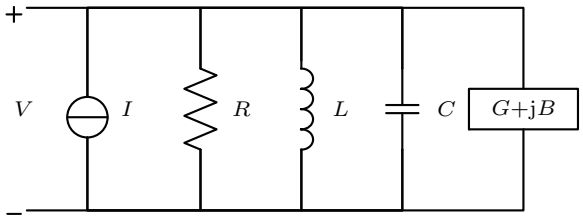


Fig. 1. Circuit model of a locked magnetron.

When they are locked, the above parameters have the following relationships: $Y = \omega c/Q$, $\omega_1 = \omega_2$, $|V| = V_1$. We substitute these relationships in Eq. (2) and assume ω as the locked frequency, ω_{01}, ω_{02} as the free-running frequencies of the two magnetrons. Then the imaginary parts of Eqs. (4) and (5) are[18]

$$\omega - \omega_{01} = -\frac{\omega}{2} Z_1 |Y_{12}| \frac{V_2}{V_1} \sin(c_1 + \theta_2 - \theta_1); \quad (4)$$

$$\omega - \omega_{02} = -\frac{\omega}{2} Z_2 |Y_{21}| \frac{V_1}{V_2} \sin(c_2 + \theta_1 - \theta_2). \quad (5)$$

From Eq. (3), $Y_{12} = 0$ means that V_2 has no effect on I_1, which leads to $\omega = \omega_{01}$ in Eq. (4). In other words, magnetron 1 becomes the master and magnetron 2 becomes the slave in this network. And the real solution of θ_2 exists if and only if

$$\left(\frac{\omega}{2} Z_2 |Y_{21}| \frac{V_1}{V_2}\right) > (\omega_2 - \omega). \quad (6)$$

When the master magnetron and the slave magnetron satisfy Eq. (6), the slave magnetron can be locked to the master magnetron with the same frequency and a constant phase difference. This is why power-combining based on the master–slave injection-locking magnetron does not need a real-time phase control system.

3. Experimental results

3.1. Power-combining experimental system

Figure 2 shows the experimental setup for the power combining of two magnetrons in which one of them is called master and the other is called slave. A manually adjustable attenuator is applied to separate and control the power used in injection and combination. A power divider is used to absorb the attenuated power so that a small amount of power from the master magnetron can propagate through a phase shifter and finally inject into the slave magnetron. Two waveguide circulators are used in the slave channel to prevent the reflected power. For the convenience of system connection, a power divider joins the attenuator and the phase shifter. Meanwhile, two magnetron outputs are combined with a waveguide combiner.

The practical configuration of this power-combining system is depicted in Fig. 3. A DC power supply from Sichuan Injet Electric CO. Ltd is used, two Panasonic continuous wave (CW) magnetrons (2M244-M1) are applied to provide two channels whose power and phase difference are measured by an AV2433 power meter and a DPO 7254 digital phosphor oscilloscope from the double directional coupler. The adjustable

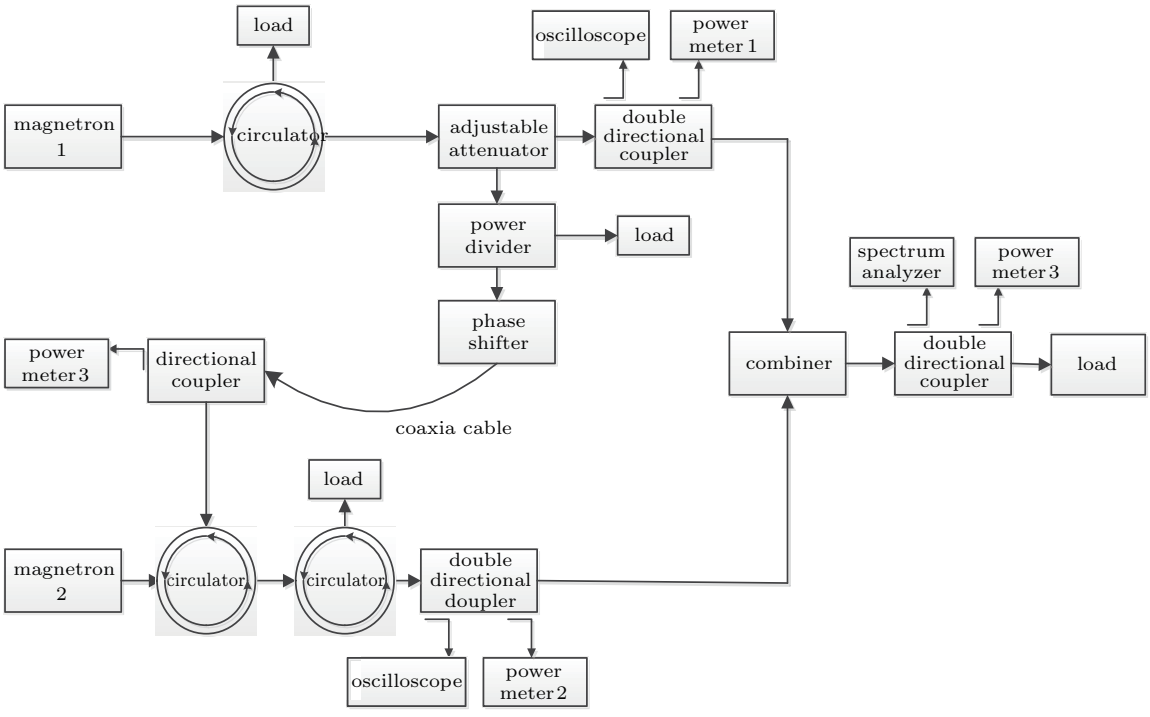


Fig. 2. Experimental system of power-combining based on master–slave injection-locking magnetron.

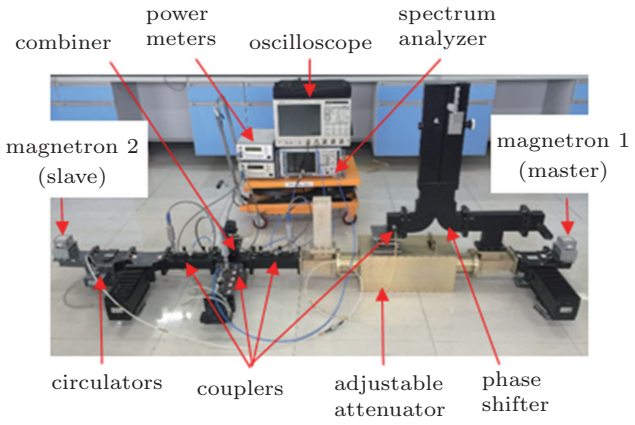


Fig. 3. (color online) Practical configuration of power-combining.

attenuator can adjust the injection power, which is measured by the power meter from the 10-dB directional coupler. The AV2433 power meter and the ROHED & SCHWARZ FSP spectrum analyzer are employed to measure the power and the spectrum of the output after power-combining. After the master magnetron output propagates through a circulator and an attenuator, most of the power injects into the combiner. The slave magnetron output is locked with the injection power from the attenuated port of the adjusting attenuator and adjusted by a phase shifter. The two sources power are combined by the combiner and finally absorbed by a load.

3.2. Power-combining with different injection power

The master magnetron oscillates at around 2.4512 GHz. With the anode current altering from 240 mA to 280 mA, the injection power changes from 0 W to 50 W. Meanwhile the power-combining source power from the master magnetron varies from 903 W to 765 W. The slave magnetron oscillates at its free-running frequency with the anode current altering from 320 mA to 280 mA so that the two sources can stay at the same power level. At the beginning of the experiment, we manually adjust the phase shifter to 135° (with which this system can obtain the highest efficiency) and keep the phase steady till the end of the experiment. As shown in Fig. 4, the outputs of the two magnetrons oscillate at their free-running frequencies respectively when the injection power is 0 W. With the increase of the injection power, the power-combining output becomes more and more close to the locked state and will finally be locked with a 50 W injection power. The power-combining efficiency along with the free-running state is present in Fig. 5. A great improvement of the combined efficiency can be achieved when the slave magnetron is close to the locked state with the increase of the injection power. This shows that the increase of the injection power improves the locking effect, bringing a higher combined efficiency.

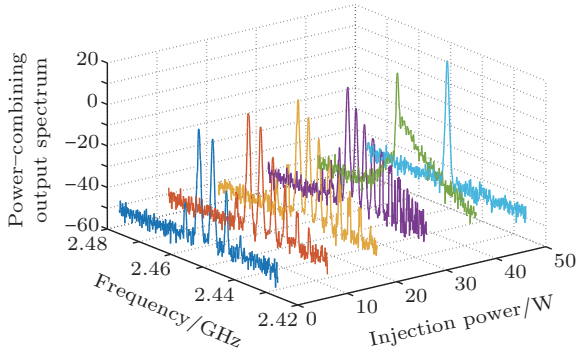


Fig. 4. (color online) Combined output spectrum with different injection power.

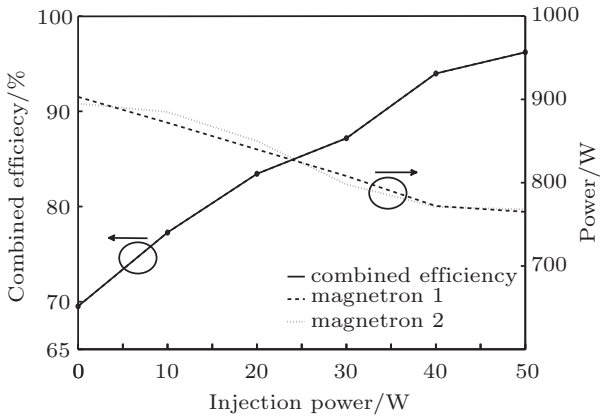


Fig. 5. Combined efficiency with different injection power.

3.3. Power-combining with different phase difference

In order to confirm the relationship between the phase and the power-combining efficiency, we first adjust the attenuator and the anode current to the state with which the injecting power is around 53 W (the slave magnetron can be locked with the master magnetron) and the source power from the master magnetron is around 780 W. The slave magnetron output is around 800 W in Fig. 6. The power-combining efficiency is changed with the phase difference altering from 0°

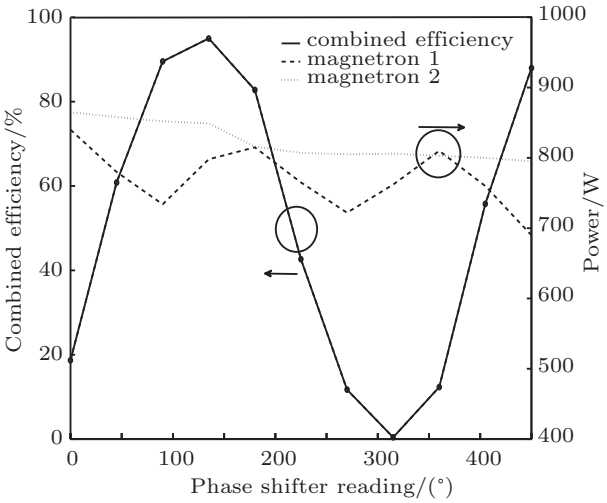


Fig. 6. Combined efficiency with the phase shifter changing.

to 450°. The phase difference between the two magnetrons is measured by the oscilloscope. Table 1 shows that the combined efficiency changes from 0.415% to 94.97% with the variation of the phase difference. Even with a small phase difference, the combined efficiency is still high. It means that the combined efficiency decreases when the phase difference increases. However, when the slave magnetron is locked, the phase difference is a constant, so we do not need to adjust too much the phase difference to obtain a high enough power-combining efficiency.

Table 1. Combined efficiency with different phase difference.

Phase difference/(°)	Phase shifter/(°)	Combined efficiency/%
–170	315	0.415
–134	270	11.72
–90	225	42.62
–35	180	82.77
10	135	94.97
45	90	89.53
48	450	87.97
88	45	60.8
90	405	55.77
135	0	18.7
142	360	12.34

3.4. Power-combining with different power difference

Noting that the master magnetron output and the injection power are 830 W and 50 W respectively, we measure the power-combining output power with different power of the slave magnetron to analyze how the sources power difference affects the combined efficiency. The anode current of the slave magnetron is adjusted from 160 mA to 340 mA in Fig. 7, and we obtain a combined efficiency up to 96.2% when the slave magnetron output power is 820 W. Note that the slave magnetron is not fully locked to the master magnetron when its power is from 400 W to 700 W. This may be because the frequency difference exceeds the locking condition when the anode current of the slave magnetron is not high enough. Figure 7 shows that only at the same power can the system get the highest efficiency and the combined efficiency decreases when the power difference increases.

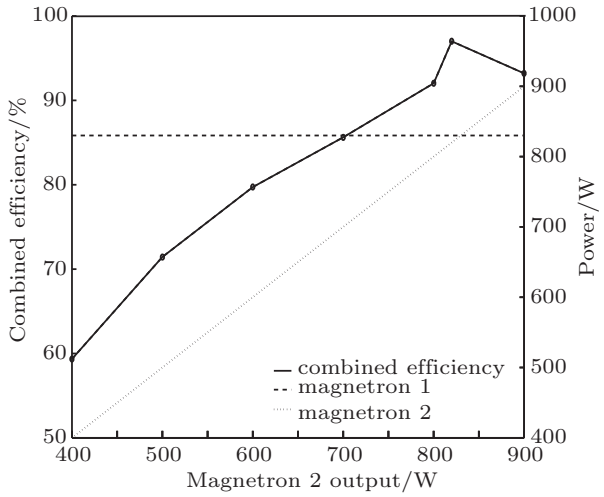


Fig. 7. Combined efficiency with different power difference.

4. Conclusion

Microwave power-combining of two Panasonic 2M244-M1 magnetrons based on a master–slave injection-locking system has been developed and studied in this paper. Experimental results show that the slaver magnetron output can completely follow the master magnetron output. The combined efficiency increases with the decrease of the phase difference and the sources power difference, and the combined efficiency is as high as 96.2%. This power-combining system is simple and less cost without the external solid-state driver and the real-time phase adjustment system. This method has great potential in developing a high power source which is cheaper and more convenient. In addition, this method provides a foundation for the power-combining based on one master and multiple slave magnetrons which will be studied in the future.

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