Phase-Shifterless Power Controlled Combining Based on 20-kW S-Band Magnetrons With an Asymmetric Injection

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***Abstract*— A real-time phase-shifterless power controlled combining based on 20-kW S-band continuous-wave magnetrons with an asymmetric injection was proposed in this letter. A high-power-capacity combiner was designed, and the behaviors of the asymmetric injection magnetrons were qualitatively characterized. The system showed a nearly 3-MHz injection-locked bandwidth and an output power control range over 3 dB at an injection ratio of 0.07. An excellent spur suppression ratio of −65.0 dBc at 500 kHz, an output amplitude stability of 0.02 dB (peak to peak), and a phase stability of ±0.9° (peak to peak) were also demonstrated. To the best of our knowledge, the power output of 34.0 kW with a total combining efficiency of 86.7% sets a new performance record for an S-band continuous wave magnetron power combining system, which is one of the best spur suppressions among all reported S-band injection locked magnetrons with an output power of over 15 kW.**

***Index Terms*— Injection-locking, magnetron, power combining, power control.**

I. Introduction

PERFORMANCE goals for high-power microwave sources in industry are currently geared towards the higher average power demanded because of the increasingly massive raw materials, and chemical reactions occurred only under specific power [1]. Owing to the physical limitations of the single oscillator's power capacity, the power output does not satisfy the requirements for high-power industrial applications. For example, the power capacity of a single continuous-wave (CW) magnetron is 20 kW at 2.45 GHz [2]. The viability of power combining of multiple oscillators has attracted significant attention, especially when each oscillator is low-cost, easily controlled and highly efficient. One of the ideal candidates for power combining in industrial applications is magnetrons,

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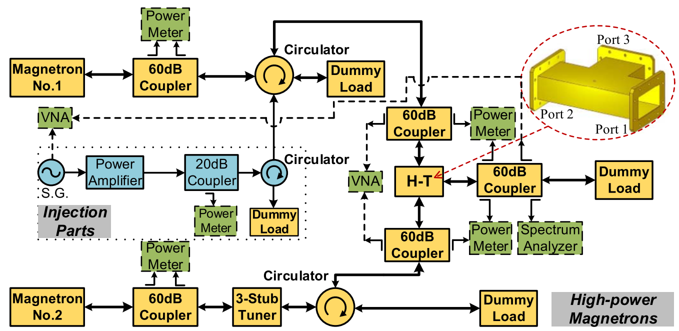

Fig. 1. Diagram of the phase-shifterless magnetron power controlled combining system.

the DC to microwave conversion efficiency of which is over 80% in the S-band [3]. Injection locking is an effective way to achieve a high output power by coherent power combining of multiple phase-controlled magnetrons [4]. Shinohara *et al.* [5] proposed an S-band high-power microwave source combining multiple external injection phased controlled magnetrons with good results for space solar power systems. Liu *et al.* [6] successfully obtained a microwave power combining of dual 15-kW S-band continuous wave external injection-locked magnetrons with a combining efficiency of 96%. However, the phase-shift networks may degrade the system performance significantly, and multiple high power injections and real-time phase controlling processes must be employed to maintain the high combining efficiencies, while there are high requirements in isolating mutual interferences among the various magnetrons. It is especially interesting for industrial processing that a real-time power-controlled method be simple and economical.

This letter presents a simple power controlled combining of dual 20-kW S-band CW magnetrons without real-time phase tuning processes, high-isolation circulators and extra power control facilities, and a relevant system was built and measured. To the best of the authors' knowledge, no such studies have been conducted to date.

II. Experiment

The block diagram of the proposed phase-shifterless power controlled combining of dual 20-kW S-band CW magnetrons system based on WR430 waveguides is shown in Fig. 1.

The industrial magnetrons used for the power combining were 20-kW water-cooled CW magnetrons (CK-2091, Sanle Microwave Co., Nanjing, China). The magnetic field intensity of the magnetron was 1250 Gs, which was supplied by an extra electromagnet with an operating DC current of 3.2 A. The power supply of the magnetron was a DC switching power supply maintained a voltage ripple of less than 1.5%. The preheating filament current required by the magnetron was 47.0 A. Once the output power of free-running magnetrons reached 15.0 kW, the cathode current was decreased to approximately 25.0 A to reduce noise and yield a narrowband spectrum [5]. The proposed method was realized in the following two steps:

Step 1: The center free-running frequency of magnetron 2 was tuned sufficiently close to magnetron 1 by changing the magnetron output reactance with the help of a 3-stub tuner [IL (Insertion Loss) ≤ 0.10 dB, HD-22WST3, HD Microwave Co., Xi'an, China].

Step 2: A signal generator (E8267C, Agilent) was amplified with a 40 dB power amplifier (YYPA4D, Sanle Microwave Co.) to provide the injection signals. The circulators (26WHPDPSC 30kW, HD Microwave Co.) with the dummy loads (KT-22W WL30kW, KT Microwave Co., Nanjing, China) transmitted the injected signals to magnetron 1 and protected the amplifier and magnetrons. An H-T with a metal rod in the middle was designed as the dual magnetrons' power combiner. Ports 1 and 2 are two input ports, and port 3 is defined as the output port, as shown in Fig. 1. The combining output microwave power was mainly absorbed by water-cooled dummy loads (Vacuum Electronics Research Institute, Beijing, China).

Five 60 dB directional couplers (IL ≈ 0.06 dB, KT22WDC-60N60KW, KT Microwave Co.) were employed to sample the high-power microwave signals for the power measurements (power meter, AV2433, the 41st Institute of CETC), the spectrum and phase noise measurements (signal analyzer, FSV40, Rohde & Schwarz), as well as for amplitude and phase measurements (vector network analyzer, E8362B, Agilent). A 20 dB directional coupler (IL ≈ 0.20 dB, SLDC-20-7F-NF, Rosenberger Co., Germany) was employed to sample the power of injection microwave signals.

III. Results and Discussion

The simulated and measured S-parameter of the designed H-T power combiner were depicted in Fig. 2(a). The output port of the power combiner was well-matched, since the return loss ($|S_{33}|$) was better than 20.0 dB. The transmission coefficient ($|S_{31}|$) was approximately −3.0 dB, and the insertion loss was less than 0.10 dB. The input reflection coefficient ($|S_{11}|$) and coupling between input ports ($|S_{21}|$) was also around −6.0 dB. The aforementioned results of the power combiner correspond to the theoretical values in [7] and [8]. Thus, the above features demonstrate that the design is valid for high-efficiency power combing, and the input microwave powers are P_1 and P_2 with a phase difference θ, the combining output power P_{out} is estimated by

$$P_{out} \approx \frac{1}{2}(P_1 + P_2) + \sqrt{P_1 P_2}\cos\theta \tag{1}$$

Equation (1) shows that the larger the input phase differences are, the lower the combining output power is, and the larger the couplings and input reflections are. It can be deuced that the efficiency is highest when $\theta = 0°$, and the combining

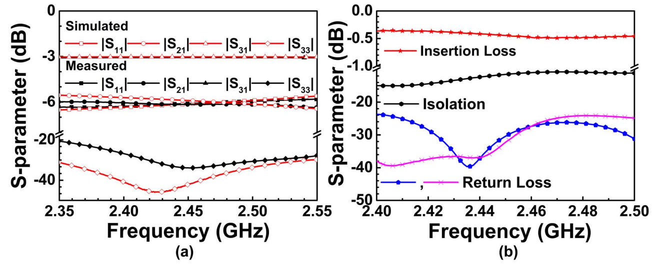

Fig. 2. (a) Simulated and experimental S-parameter of the designed H-T combiner, (b) Measured S-parameter of a circulator (high-power path).

power is $1/2 \cdot (P_1 + P_2)$ when $\theta = 90°$, which means that no combining effect occurs when $P_1 = P_2$.

The measured typical S-parameter of a circulator was depicted in Fig. 2(b). All return losses of the high-power path were better than 20.0 dB, and the insertion loss was approximately equal to 0.37 dB. The isolations varied from 11.0 to 15.0 dB in the subsequent experimental bandwidths. Thus, the circulator and power combiner cannot isolate the mutual couplings effectively. Consequently, the remaining coupling parts of the designed power combiner through the low-isolated circulators acted as the mutual injection signals. Based on the analysis of mutual injection magnetrons [9]–[11], the governing equation for the phase differences of mutual injection magnetrons is determined by following formula:

$$\omega_{final} = \omega_i \left[1 - \frac{\xi_{ij}}{2Q} \cdot \frac{A_j}{A_i} \sin(\Phi_{ij} + \varphi_i - \varphi_j)\right] \tag{2}$$

$$\begin{aligned}\frac{d(\varphi_1 - \varphi_2)}{dt} &+ (\omega_1 - \omega_2)\\ &= \frac{\xi_{12}}{2Q_1} \cdot \frac{A_2}{A_1}\sin(\Phi_{12} + \varphi_1 - \varphi_2)\\ &\quad - \frac{\xi_{21}}{2Q_2} \cdot \frac{A_1}{A_2}\sin(\Phi_{21} + \varphi_1 - \varphi_2)\end{aligned} \tag{3}$$

where $i \neq j$, $i = 1$, 2 and j = 1, 2, and A_i, φ_i, Q_i and ω_i are the amplitude, phase, external Q-value and free running frequency of the magnetron i when the other is shut down, respectively. $\xi_{ij} \cdot exp(j\Phi_{ij})$ represents a complex coupling coefficient between magnetron i and magnetron j.

As calculated from (1), the high-efficient power combining requires a constant phase between two magnetron outputs, which is $\varphi_1 = \varphi_2$. Equations (2) and (3) illustrate that if the magnetrons' frequencies lie within locking bandwidths, the magnetrons eventually oscillated at a common frequency with the specific phase differences roughly constant. Similarly to the work of Shinohara *et al.* [5] or Slater [12], since the mutual couplings are reciprocal and symmetric, and the external Q factors of the magnetrons are nearly equal, a constant phase synchronization ($\varphi_1 = \varphi_2$) can be synthesized at the frequency ω_{final} by the following free-running frequencies relationship:

$$\omega_1 \approx \omega_2 \tag{4}$$

As a result, by carefully tuning the 3-stub tuner (step 1), the magnetrons were operating at 2.4475 GHz (magnetron 1: anode voltage of −11.59 kV and anode current of 2.26 A) and 2.4480 GHz (magnetron 2: anode voltage of −10.54 kV and anode current of 2.37 A), and the corresponding average powers were 19.9 kW ($P_{mag.1}$) and 19.3 kW ($P_{mag.2}$), respectively, as shown in Fig. 3. It could be seen that random

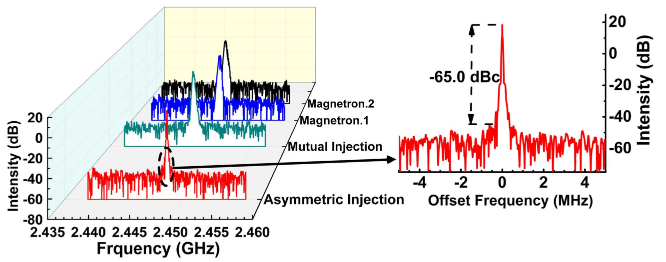

Fig. 3. Spectrums of outputs at different states (RBW: 50 kHz, VBW: 50 kHz).

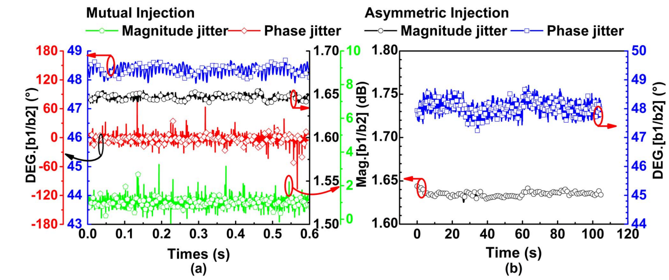

Fig. 5. Relative amplitude and phase jitters at 2.4465 GHz.

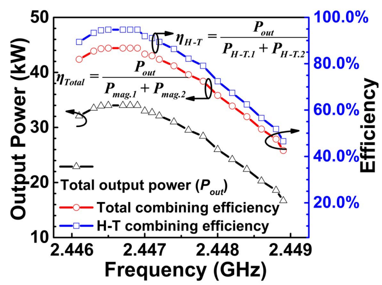

Fig. 4. Outputs and combining efficiencies with various injection frequencies in the locking region.

frequency fluctuations were visible during single magnetron free-running operation, and the spectrum of the free-running magnetron may shift with respect to time.

When the magnetrons ran simultaneously, magnetron 1 received a total injected power of 107.9 W, and magnetron 2 received a total injected power of 156.0 W. The differences of the coupled powers were primarily caused by the magnetrons' different load-pull characterizations and the circulators' inconsistency [13]. The resultant synthesized frequency shown in Fig. 3 was 2.4465 GHz, which was lower than the free-running frequencies of both magnetrons because of the unequal mutual couplings [10], [14]. Meanwhile, the synthesized frequency showed no obvious frequency variation, and a relatively sharp frequency spectrum.

When magnetron 1 was externally injected with the power of 100.0 W (injection ratio 0.07, step 2), magnetron 2 was also synchronized with the external signal via mutual injections, and vice versa. Fig. 4 depicts that all microphonic signals and frequency chirps disappeared in the final output, and the frequency spectrum was sharper than in the above states. The final output spur suppression improved visibly, and the spur suppression ratio was measured to be −65.0 dBc @ 500 kHz, which is a significant improvement compared with our previous values and relevant reports [1], [6].

For the abovementioned injected magnetron, the phase difference ($\Delta\varphi$) between two magnetrons is expressed by

$$\Delta_{\varphi} = \sin^{-1}\left(2Q_1\frac{\mathrm{A}_1}{\mathrm{A}_{inj}}\cdot\frac{\omega_{inj}-\omega_{final}}{\omega_{final}}\right) \tag{5}$$

Therefore, tuning the injected frequency is an effective way to control output powers in real time. In consideration of insertion losses of circulators and mutual couplings [11], the microwave powers delivered to the designed H-T combiner were 18.1 kW ($P_{H-T.1}$) and 17.8 kW ($P_{H-T.2}$), respectively. The initial mutual coupling magnetrons achieved a power output of 32.1 kW with a total combining efficiency of 81.9% ($\eta_{H-T} = 89.4\%$). The average power was nearly constant, which coincided well with the estimation in [15]. After introducing the asymmetric injection, the associated combining output powers and efficiencies with varied injected frequencies were measured in Fig. 5. An asymmetric injection locked bandwidth reached nearly 3.0 MHz. An output power control range exceeded 3.0 dB and no combining effects occurred beyond the locking areas. The total combining efficiency remained above 80.0% ($\eta_{H-T} \geq 85.0$ %) for an injection bandwidth of 1.3 MHz, and the maximum output was 34.0 kW with a total combining efficiency of 86.7% ($\eta_{H-T} = 94.7\%$).

The amplitude and phase jitters were monitored by a vector network analyzer, as shown in Fig. 1. Fig. 5(a) shows the measured relative amplitude and phase jitters for approximately 600 ms at 2.4465 GHz. In the absence of an asymmetric injection (mutual injection mode), the peak-to-peak amplitude jitter was reduced to ±1.50 dB, and the magnetron output phase differences uniformly distributed on both sides of 0° along with the peak-to-peak phase shift of the magnetron output was compressed to ±120° for the single frequency at 2.4465 GHz. Such jitters were primarily caused by the shaking of mutual injected couplings [14], [15]. Meanwhile, the peak-to-peak amplitude was nearly constant (less than 0.01 dB), and the peak-to-peak phase shift of the output was reduced from ±120° to ±0.6° for approximately 600 ms when both magnetrons were injection-locked by the asymmetric injection. Also, long-term data at approximately 100 s was used to demonstrate the amplitude and phase jitter of the system, as shown in Fig. 5(b). The peak-to-peak amplitude and phase jitters were 0.02 dB and ±0.9° respectively, which shows an increase in relative jitters and a significant improvement compared with values reported in the literature [1], [3], [5], [6], [14], [15].

IV. Conclusion

Microwave power combining based on dual 20 kW continuous wave magnetrons in S-band with a real-time power control was proposed and presented. A nearly 3.0-MHz injection locked bandwidth was achieved, and an output power control range of over 3.0 dB was obtained by tuning the injection frequency when the total injection power was fixed at 100 W. An excellent spur suppression ratio of −65.0 dBc @ 500 kHz, an output amplitude stability of 0.02 dB (peak to peak), and a phase stability of ±0.9 degrees (peak to peak) were achieved, as well. To the best of the authors' knowledge, this report describes one of the highest output powers and spur suppression ratios ever reported for an S-band continuous-wave magnetron power combining system.

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