Microwave power combining system based on two injection-locked 15 kW CW magnetrons

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Microwave Power Combining System based on Two Injection-locked 15 kW CW Magnetrons

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Abstract — A microwave power combining system based on two 15 kW continuous wave magnetrons has been developed and studied. A high power coherent microwave output is required in industrial applications. This system includes two injection-locked S-band 15 kW continuous wave magnetrons. The coherent microwave power combining technique is applied to the experiments. The phase of one magnetron output is controlled by a digital phase shifter, and the phase difference of two magnetron power outputs is monitored by a phase detector. A program is applied to automatically adjusting the microwave power combining process. The experimental combining efficiency is over 96%.

Index Terms — Microwave power combining, injection-locked CW magnetron, phase adjustment, automatic control.

I. Introduction

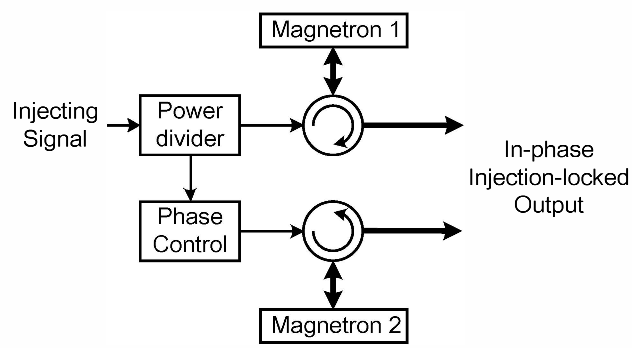
Continuous wave magnetrons are commonly applied to industrial microwave heating, radar, microwave power transmission [1].A single magnetron usually does not meet the high power capacity requirement for the special industrial application, e.g. the diamond film from microwave plasma chemical vapor deposition [2] and Space Solar Power Satellite/Station (SSPS) [3]. The combining of multi-magnetrons output is a valid method to gain a high power source, and this technique has been discussed in the SSPS [4, 5]. The microwave power combining efficiency is more sensitive with the frequency and phase difference between the magnetron outputs. Different magnetron has different frequency characteristic. The direct combining efficiency of multi-magnetron is not high enough. The injection-locking technique is a key method to gain a magnetron output with a stable adjustable phase characteristic [6-8]. The coherent power combining technique is applied to the microwave power combining of multiple injection-locked magnetrons.

In this paper, Two 15 kW injection-locked CW magnetrons are the basis of the microwave coherent power combining experiment. Two 15 kW CW magnetrons are injected by a given frequency microwave signal, and locked at given frequency of the injecting signal. A virtual instrument software program is applied to the phase control and monitoring a gain/phase detector. According to the results of the phase detector, the program adjusts the phase shifter until observing the optimum power combining efficiency.

II. Injection-locked Magnetron

The theory of injection locking of magnetron has not been conformed until today. The injection-locking of relativistic magnetron has been studied many years [9]. The injection-locking of CW magnetron attracts a lot of interests in recently because the industrial application and microwave power transmission in SSPS. The basic principle of the injection-locking of a magnetron is explained as a free-running magnetron responding to a tunable external injection signal, with which the phase and frequency of the output of the magnetron synchronized after instantaneously sophisticated interaction.

First of all, the frequency of injecting signal should be at a given frequency close enough to the free-running frequency of the magnetron [10], which is applied to locking the magnetrons. Before the microwave power combining, two CW magnetrons should be injecting locked at the same given frequency. A coherent injecting signal is applied to lock the two magnetrons as shown in Fig. 1. An injecting signal is divided into two coherent signals by a power divider, and injected into two magnetrons, respectively. The phase of one way coherent signal is controlled and then injected into the second magnetron. The locked phase of the second magnetron output is adjustable and is prepared for the microwave power combining. According to an adjustment control program, the two magnetron injection-locked output is in phase in ideal conditions.



(a)

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(b)

Fig. 1. (a) The diagram of two injection-locked magnetrons applied to microwave power combining system; (b) The 15 kW magnetron

III. EXPERIMENTAL SYSTEM

The block diagram of two way injection-locked 15 kW CW magnetrons microwave power combining system is shown in Fig. 2. The magnetron power supply system is used to supply two 15 kW magnetrons (as the red line connected). Two 60 dB directional coupler 1 and 2 are used to measuring the phase difference of the two magnetron system and the output power of each magnetron. A four-port circulator is applied to protect the magnetron and isolate the injecting signal and the large power microwave output. Two magnetron outputs are combined through a waveguide power coupler. A 60 dB directional coupler 3 is applied to spectrum observation and power measurement of the microwave power combining output signal. Additionally, the coherent injecting signal are amplified and injected into the magnetron through a waveguide circulator, respectively (as the purple line shown). The phase adjustment and the phase difference detection of microwave power combining are controlled by a computer (as the green line shown).

In this experiment, the injecting signal is provided by a Hittite HMC-T2220 microwave source, which is also applied to adjusting the frequency of the injecting signal. The magnetrons are made by Nanjing Sanle Electronic Information Industry Group. Co. LTD. The magnetic field of the magnetron is supplied by an extra electromagnet, which is also supplied from the magnetron power supply system. The frequency spectrum and the output power are monitored by a Rohde&Schwarz FSP (9 kHz-7 GHz) frequency spectrum analyzer and three AV2433 microwave power meters, respectively.

The phase detector is designed with a RF/IF gain/phase detector MMIC chip AD8302. The output of the phase detector provides an accurate measurement of phase over a 0°–180° range scaled to 10mV/degree. The operating results are monitor by the computer. The phase shifter is designed with a 6 bit digital phase shifter MMIC chip MAPS-010164. The minimum phase shift step is 5.6°. The phase shifter is applied to adjust the phase of one way injection signal. The digital control signal of phase shifter is controlled by the computer too. The phase difference between two magnetron outputs is sensitive to the power combining efficiency. If the phase of two magnetron outputs is opposite, the power combining efficiency is lowest.

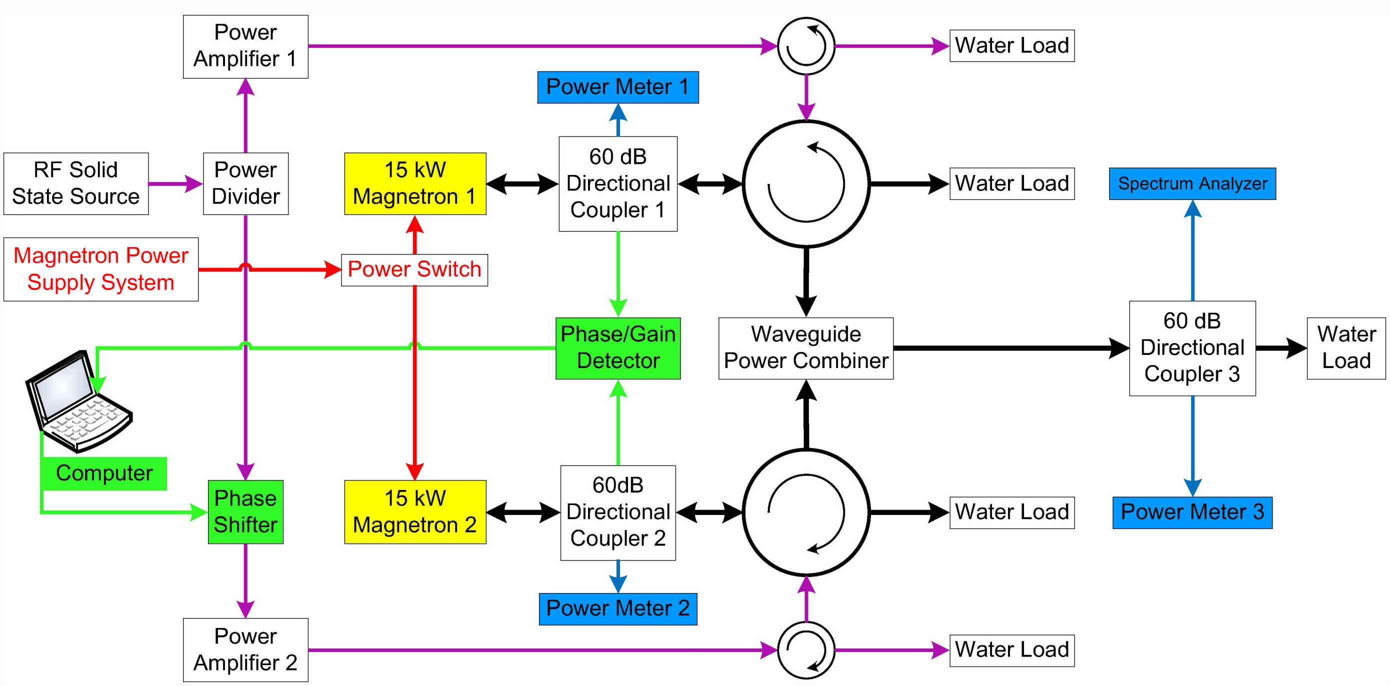

Fig. 2. The block diagram of two way injection-locked 15 kW CW magnetrons microwave power combining system.

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The two magnetrons are locked at the same frequency 2441 GHz by the coherent injecting signals, respectively. The microwave power combination of two way injection-locked magnetrons is accomplished by this experiment apparatus. The virtual instrument technology is applied to the software control system of this experimental system. Fig. 3 shows the display window of the software control system, including the display of the frequency of the injecting microwave signal, and the voltage waveform image of the phase detector results.

The control system is applied to monitoring the phase difference of the two magnetron outputs and then adjusting the phase shifter to gain a better combining efficiency. The whole process is monitored by a computer, and an oscilloscope is applied to measuring the real-time phase of the outputs from the magnetrons. In this experiment, the phase detector collects and compares the phase difference of two magnetron outputs. The phase of one injecting signal is adjusted in time to obtain the optimum power combining efficiency. The computer judges the phase difference and control the phase shifter until an optimum power combining efficiency gained.

The experiment results of the microwave power combining of two injection-locked 15 kW CW magnetrons are shown in table I. The combining efficiency is over 96%. The best combining efficiency is up to 96.7%. The combining power is observed from power meter 3 (as shown in Fig. 2.), which is changing in time with the adjustment of the phase shifter.

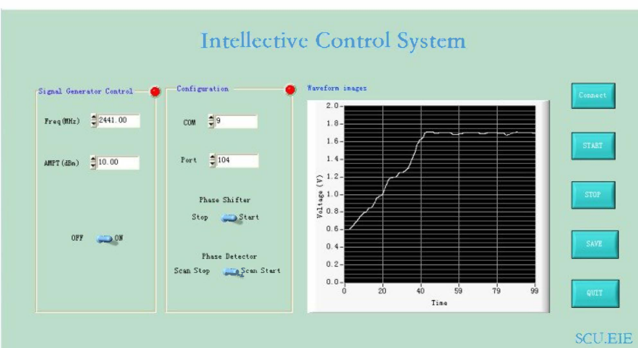

Fig. 3. The display window of the software control system.

TABLE I

Measurement Results

No.	Power of Magnetron A (kW)	Power of Magnetron B (kW)	Combining power (kW)	Combining Efficiency
1	12.9	13.7	25.6	96.4%
2	13.1	14.1	26.2	96.4%
3	13.0	13.9	24.2	96.0%
4	13.1	14.1	26.3	96.7%

IV. Conclusion

The power combining system based on two injection-locked 15 kW CW magnetrons is set up and studied. The experimental results of microwave power combining are presented in this paper. The combining efficiency is greater than 96%. This experiment is useful to achieve a large power microwave coherent source, which meets the requirements of a certain industrial application and is less expensive than other vacuum high power microwave apparatus. The injection-locking mechanism of the magnetron and microwave power combining should be studied in the future.

Acknowledgments

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References

[1] S. Sasaki, K. Tanaka, and K. I. Maki, "Microwave Power Transmission Technologies for Solar Power Satellites," Proceedings of the IEEE, vol. 101, pp. 1438-1447, 2013.

[2] P.-C. Huang and M.-S. Wong, "Nanostructures of mixed-phase boron nitride via biased microwave plasma-assisted CVD," Vacuum, vol. 100, pp. 66-70, 2014.

[3] N. Shinohara and H. Matsumoto, "Design of space solar power system (SSPS) with phase and amplitude controlled magnetron," in Radio Science Conference, 2004. Proceedings. 2004 Asia-Pacific, 2004, pp. 624-626.

[4] T. Mitani, N. Shinohara, and H. Matsumoto, "Development of a pulse-driven phase-controlled magnetron," presented at the Eighth IEEE International Vacuum Electronics Conference, 2007.

[5] N. Shinohara, H. Matsumoto, and K. Hashimoto, "Solar power station/satellite (SPS) with phase controlled magnetrons," IEICE transactions on electronics, vol. 86, pp. 1550-1555, 2003.

[6] I. Tahir, A. Dexter, and R. Carter, "Frequency and phase modulation performance of an injection-locked CW magnetron," IEEE Transactions on Electron Devices, vol. 53, pp. 1721-1729, Jul 2006.

[7] P. Pengvanich, "Theory of injection locking and rapid start-up of magnetrons, and effects of manufacturing errors in terahertz traveling wave tubes," The University of Michigan, 2007.

[8] T. Mitani, N. Shinohara, and K. Hashimoto, "A Fundamental Study on Spectral Purity of a CW Magnetron for Microwave Power Transmission," presented at the XXIX URSI General Assembly, 2008.

[9] J. Benford, R. R. Smith, H. Sze, B. Harteneck, and W. Woo, "Phase-locking of relativistic magnetrons," in 1988 Los Angeles Symposium--OE/LASE'88, 1988, pp. 23-27.

[10] R. Adler, "A study of locking phenomena in oscillators," Proceedings of the IRE, vol. 34, pp. 351-357, 1946.

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