Stabilization of Phase and Frequency of an S-Band Magnetron by Injection Locking

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Abstract: *We demonstrated feasibility of magnetron as a promising candidate for the microwave power units constituting a phased array system which enables long distance wireless power transfer, by stabilizing phase and frequency of an S-band magnetron.*

Keywords: *wireless power transfer, magnetron, phase, frequency, stabilization*

Introduction

To make the space solar power system (SSPS) economically feasible that transfers electric power wirelessly via microwave to the earth after the sunlight generation on the geostationary orbit, high-power microwave module with the lowest weight-power ratio and the highest DC-RF power conversion efficiency, is required.

Magnetron, widely adapted in various fields, such as microwave ovens, radars and accelerators, is a promising source satisfying both of the requirements that solid-state devices cannot. Shortcomings, however, such as unstable phase and poor frequency stability, prevent magnetrons from being used for phased array system forming a spatially confined energy beam and controlling the direction of the beam precisely to realize long distance wireless power transfer systems including SSPS. [1-2]

In this presentation, we demonstrate extreme stabilization of phase and frequency of an S-band magnetron by injection locking to prove the feasibility of magnetron for phased array.

Frequency Stabilization

A commercial S-band magnetron (1.28kW CW – 2M137) and a switching mode power supply (SM 445) were used for demonstration.

Figure 1 shows the spectral transition of the magnetron from default operation to operations with additional measures. It is clear that the spectral purity is significantly enhanced (the noise floor becomes lower, the side bands are disappeared and the linewidth of the main signal becomes narrower) by taking more measures. [2-3] The switching noise of 76 kHz from the power supply energizing the magnetron anode was further suppressed by injection of external pure reference of 10 W.

Figure 2 shows an example of frequency control by the external injection and frequency locking range with respect to the injection power. Frequency is locked within 0.5% (~12MHz) of the center frequency with appropriate injection power.

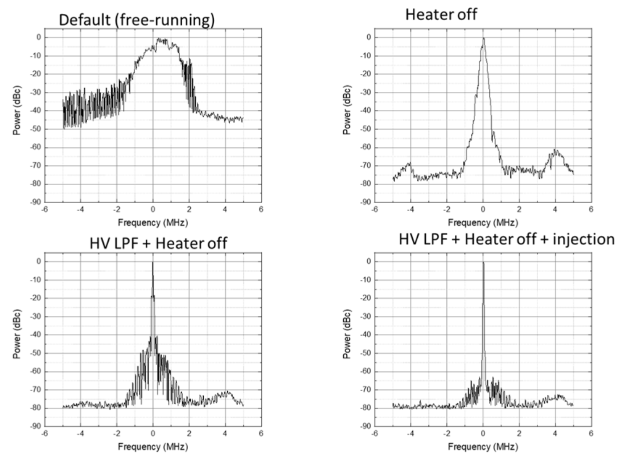

Fig. 1. The summary of spectral characteristics of the magnetron in case of default (free-running with heater power), heater-off, employment of high-voltage (HV) low pass filter (LPF) without heater, and injection locking under previous conditions.

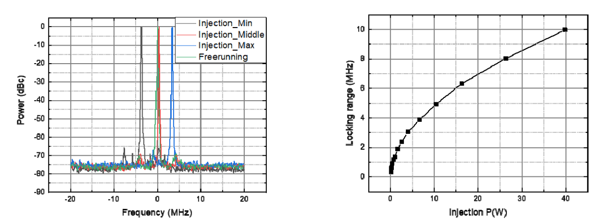

Fig. 2. Left: Example of frequency control by injection. Right: Frequency locking range with respect to the injection power at the operation of 80% of the maximum power.

Phase Stabilization

Schematic diagram of the phase locking loop (PLL) to control and stabilize the phase of the magnetron is depicted in Fig. 3. The basic idea of PLL is similar to the previous studies. [3-4] The part of PLL circuit (green box in Fig. 3) consists of a power divider distributing microwave reference to a phase shifter locking the phase of the magnetron in the desired one and a double balanced mixer detecting the phase difference between the reference signal and the magnetron, and a control circuit producing the voltage to adjust the phase of the phase shifter accordingly.

Figure 4 and 5 show the schematic diagram of the control circuit and a fabricated PCB of the part of PLL, respectively. The overall response time of the PLL was assumed to be about 200 ns considering the filling time of electrons in the magnetron resonator.

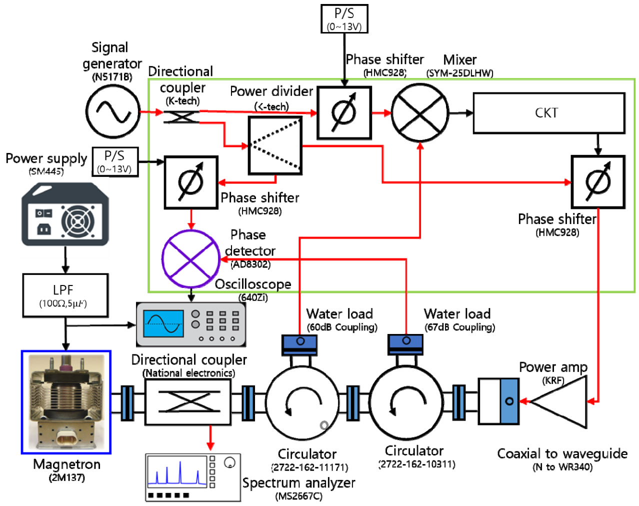

Fig. 3. Experimental configuration for injection locking with the phase locking loop (PLL). PLL mainly consists of a double balanced mixer detecting the phase difference between the reference and the magnetron and a control circuit (CKT) producing the voltage to adjust the phase of the phase shifter.

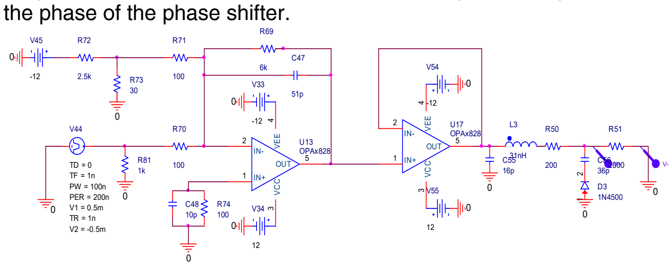

Fig. 4. The schematic diagram of the CKT. The voltage to adjust the phase is produced by the inversion amplifier and offset bias, then applied to the phase shifter through the buffer. The operational amplifiers employed in the PLL has 150V/µs of slew rate and 45 MHz of open gain bandwidth. Resistances and capacitances were determined considering the circuit response and optimized by PSpice simulation.

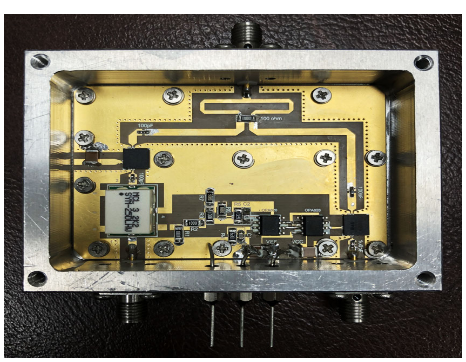

Fig. 5. Fabricated PCB of the part of PLL, corresponding to the green box region in Fig.3.

By constructing the experimental setup employed with the fabricated PCB according to the schematic (Fig. 3), the phase of the magnetron was stabilized to the extreme as shown in Fig. 6 and 7. The phase of the injection locked magnetron was adjusted from -180°to 180°by the phase shifter inserted in front of the double balanced mixer.

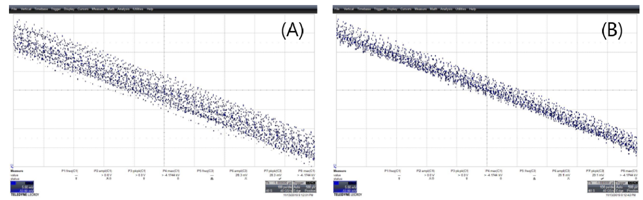

Fig. 6. Jittering of magnetron oscillation in case of (A) injection only and (B) PLL over the time span of 1 ns (corresponding to about 15°in phase, where the signals of the magnetron oscillation were down-converted to 41 MHz by a mixer and a precise reference.)

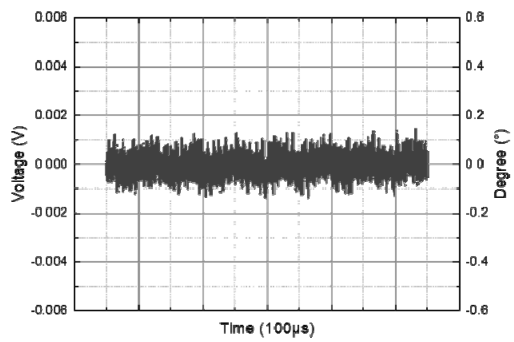

Fig. 7. Phase stability (about 0.3°peak-to-peak) of the injection locked magnetron with PLL at the 80% of the maximum power (>800 W) after averaging out thermal noise. Long-term (> 0.5 s) drift of the phase within 0.24°(root-mean-square) was observed, which is exact replication of the anode-voltage variation to maintain the anode-current at a constant value.

Conclusion

Extreme stabilization of phase (about 0.3° peak-to-peak) and frequency (below -60 dBc of noise floor) of an S-band magnetron driven by the power supply with further suppressed switching frequency of 76kH without heater power, was realized by locking with external signal along with PLL. This magnetron capable of controlling frequency and phase stably could satisfy the tight requirements of the phased array system for a long-distance microwave wireless power transfer.

Acknowledgment

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