Suppression of a Long-Term Instability of a Commercial Magnetron with Low-Ripple DC Power Supply for Heater

Tae-Hyun Kim1,2, Chang-Seung Ha1, Sung-Roc Jang1,2, Member, IEEE, Jong-Soo Kim1, and Seong-Tae Han1,2, Senior Member, IEEE

1Electrophysics Research Center, Korea Electrotechnology Research Institute, Changwon, Gyeongnam 51543 Korea
2Energy and Power Conversion Engineering, University of Science and Technology, Changwon, Gyeongnam 51543 Korea

Corresponding author: Seong-Tae Han (e-mail: saiph@keri.re.kr).

This research was supported by the KERI Primary research program of MSIP/NST (No. 21A01064)

ABSTRACT Compact but powerful and efficient magnetrons are in service for various high-power microwave applications owing to their additional superiority of low-cost mass production. However, the magnetron’s inherent instability in frequency and phase over a relatively wide spectrum limits the versatile availability of the magnetron for possible advanced applications, including a long-distance wireless power transfer system (WPTS) that employs the magnetron as a unit source of a phased array system. The authors present a methodology suppressing a long-term instability of the S-band commercial magnetron harnessed by the phase-locking-loop (PLL) injection controlling and fixing the phase and frequency of the magnetron to the extent of the precision for a WPTS. The long-term drift of the phase exactly replicating the anode voltage fluctuations is successfully suppressed by the implementation of a DC power supply to compensate the cooling effects of the heater, which contributes to extreme stabilization of the phase (peak to peak 0.2°) for high-power (1kW). And eligibility for the unit source of a phase-arrayed WPTS is proven by varying the output power while maintaining the phase at a constant.

INDEX TERMS Magnetrons, Noise, Phase-locking-loop (PLL), Series parallel resonant converter (SPRC), Cooling effect

I. INTRODUCTION

Magnetron is a diode tube that generates a high-power microwave using the interaction of spokes of rotating electrons under a magnetic field with a series of cavity resonators. Compact but powerful and efficient magnetron has provided radars since World War II with operational improvements in resolution and range. There are even today thousands of magnetron aviation and marine radar units in service. However, the magnetron’s inherent instability in frequency and phase over a relatively wide spectrum limits the availability of the magnetron for possible advanced applications. Instead, industrial implementation of magnetrons flourishes in consumer microwave ovens and commercial ovens for baking and drying, generation of processing plasmas, industrial heating, and chemical process intensification [1]-[5] owing to additional superiority of low-cost mass production.

In recent years, an intensive search for a high-power microwave module capable of (a) a few grams per unit power in the weight-power ratio and (b) 70% or higher in the DC-RF power conversion ratio, has been conducted to realize long-distance wireless power transfer systems, including the space solar power system (SSPS) that transfers electric power wirelessly via microwave to the earth after the sunlight generation on the geostationary orbit targeting from the 36,000 km above to the diameter of 100m [6]-[12]. A magnetron is a competitive source satisfying both of the requirements, (a) to reduce launch costs and (b) to maximize energy utilization and to minimize thermal loss, among various microwave modules [13]-[15]. To employ the magnetron as a unit source of a phased array system forming a spatially confined energy beam and controlling the direction of the beam precisely, researchers including the authors have studied methodologies controlling and fixing the phase and frequency of a magnetron to the extent of the
precision required for a phased array antenna or a linear accelerator overcoming the critical and inherent shortcomings of magnetrons [16]-[22].

Previous studies on the noise in high-power microwave tubes [23]-[25] concluded that the noises on the electron beam play an important role, which is mainly attributed to the technical parameters such as beam current and voltage near their nominal values. Fluctuations in the beam parameters can be caused by the finite stabilization of the switching mode power supply (SMPS) for high acceleration voltage and the power supply for heating the electron emitter. Compared to the gyrotron, so-called, electron cyclotron resonance maser [26], [27], the magnetron is not highly resonant device so that the frequency and phase of a magnetron are more strongly influenced by the driving power supplies. In the previous study [28], however, the noises in the frequency and phase of a commercial 2.45GHz magnetron were successfully suppressed with the low pass filter installed to the output of the SMPS driving the magnetron and the phase-locking-loop (PLL) assisted injection. As a microwave power module [29]-[32], the PLL injection harnesses the magnetron on the basis of noise suppression of the driving power supply when the power supply heating the emitter is off to remove the noise. The authors, however, could not but report the long-term drift of the voltage from the phase detector and the anode voltage, where the voltage from the phase detector is the exact replication of the anode voltage. Such a long-term drift may be attributed to emission cooling of the cathode surface [33]-[39] or the conduction cooling of the cathode due to insufficient thermal insulation of the heater.

In Sec. II, we report details of the analysis, design, and implementation of the driving power supplies, which include a DC heater power to compensate the cooling effects on the cathode emitter and a high-voltage source with the combination of a high switching frequency and a low pass filter to reduce ripple and switching noise effectively. Long-term stabilization of the phase and frequency of the magnetron harnessed by the PLL and driven by the developed power supplies is demonstrated in Sec. III. Eligibility for the unit source of a phase-arrayed power-transfer system is proven by varying the output power with the driver while maintaining the phase at a constant. Conclusion follows in Section IV.

II. DESIGN AND IMPLEMENTATION OF POWER SUPPLIES

Figure 1 shows a schematic configuration of the magnetron system harnessed by the PLL and driven by the power supplies. Table I shows specifications of (a) the cathode power supply (CPS) to extract and accelerate electrons from the cathode to the anode and (b) the heater power supply (HPS) to warm up the cathode to the temperature for thermionic emission of electrons. As aforementioned, decreasing output voltage ripple and switching noise of the power supplies improve phase stability of the magnetron. These requirements can be met by increasing switching frequency of the power supplies and applying an output low pass filter (LPF). In this paper, resonant converter, widely used in high frequency applications due to zero voltage switching (ZVS) characteristic, is adapted [40]-[42]. Reduced switching losses enable power supplies to operate at high switching frequency and to decrease switching noise. Considering the output voltage ripples at a small-power condition, we employed the continuous conduction mode (CCM), where switching frequency increases at light load operation, in design instead of the discontinuous conduction mode (DCM). Among various types of resonant converters, a series-parallel resonant converter (SPRC), which can take benefits of a series resonant and a parallel resonant converter, is employed [43]. An LLC resonant converter capable of achieving high efficiency, has been widely used. However, designing an LLC converter with high efficiency for dynamic loads requiring high voltage is difficult as discussed in [44], [45]. (For high voltage applications, high step-up transformers are essential. However, parasitic components of high step-up transformers cause difficulties in designing the

| TABLE I |
| SPECIFICATIONS OF DEVELOPED POWER SUPPLIES |
| **CATHODE POWER SUPPLY** |
| Three phase AC Input Voltage | 380 V<sub>ac rms</sub> |
| Rectified DC Voltage, V<sub>m</sub> | 513 V |
| Switching Frequency, f<sub>sw1</sub> | 435 kHz |
| Maximum Output Power, P<sub>o,max</sub> | 2.5 kW |
| Maximum Output Voltage, V<sub>o,max</sub> | 5 kV |
| Maximum Output Current, I<sub>o,max</sub> | 500 mA |
| Maximum Efficiency, η<sub>max</sub> | 96 % |
| **HEATER POWER SUPPLY** |
| Input DC Voltage, V<sub>m</sub> | 12 V |
| Switching Frequency, f<sub>sw2</sub> | 250 kHz |
| Maximum Output Power, P<sub>hps</sub> | 90 W |
| Maximum Output Voltage, V<sub>hps</sub> | 6 V |
| Maximum Output Current, I<sub>hps</sub> | 15 A |

![FIGURE 1. Schematic diagram of the experimental system: PA stands for power amplifier, PLL for phase-locking loop, CPS for cathode power supply, and HPS for heater power supply, respectively.](image)
LLC resonant converter and its light load operation.) Therefore, an LLC resonant converter utilizing parasitic components as a resonant tank is employed instead of the LLC converter. In addition, by shaping resonant current as a trapezoid in the LCC, the RMS value of the resonant current decreased, which contributes to reducing conduction losses of the entire circuit [46], [47]. With mentioned advantages of the LLC resonant converter, the developed CPS achieved a maximum efficiency of 96% and the output voltage ripple of 0.4%.

A. DESIGN CONCEPT OF CPS AND HPS

1) COMPOSITION OF EACH POWER SUPPLIES

Figure 2 shows circuit diagrams of the CPS and the HPS. The CPS consists of a half Bridge Inverter (S1-S2), a resonant tank (\(L_{r1}: \text{series resonant inductor, } C_{r1}: \text{series resonant capacitor, } C_{p1} [C_{p2}-C_{p10}]: \text{parallel resonant capacitor}\), a main transformer (TR1), a voltage doubler (\(D_{rec1}-D_{rec10}, C_{p2}+C_{p10}\)). The voltage doubler has the advantage of implementing a transformer owing to the reduced number of secondary side winding and insulation. In the case of the HPS, a full-bridge inverter (S1-S4) for low stresses of switches and a center-tapped transformer (TR2) rectifier are applied. Since the HPS has low output voltage, the center-tapped structure reduces forward voltage drops compared with the one by a full-wave rectifier. In the case of the full-wave rectifier, there are two diodes in the current path. On the other hand, only one diode induces the forward voltage drop in the center-tapped full-wave rectifier.

To operate the CPS safely, an interlock control method is applied to controlling the power. Since the interlock control enables to gradually release the control voltage (\(V_{\text{com}}\)) by comparing reference signals (\(V_{\text{ref}}, V_{\text{rec}}\)), the CPS can avoid rapid change of the dynamic load, i.e. magnetron [48], [49]. The HPS that employs the same control strategy maintains rated power operation (43W) until the CPS reaches to required output. After that, the output power of the HPS is controlled and kept low (3W) by the power control loop to compensate the cathode cooling effect. As a result, increased switching frequency due to the small power operation improves output voltage ripple.

2) OUTPUT LOW PASS FILTER

Output LPFs are implemented for both the CPS and the HPS to reduce the output voltage ripples and the switching noises. In the case of the CPS, high output voltage makes it hard to increase the capacitance of the filter capacitor. Therefore, the LPF of the CPS consists of a 230\(\mu\)H inductor and a 240\(n\)F capacitor. In the case of the HPS, 50\(\mu\)H and 6.6\(\mu\)F are used. Cut-off frequencies of each LPFs are designed to be less than one-twentieth.

B. TRAPEZOIDAL APPROXIMATION AND PARAMETER DESIGN

![FIGURE 2. Circuit diagrams of the CPS and the HPS based on series parallel resonant converter: (a) The CPS including a half-bridge inverter and a voltage doubler (b) the HPS including a full-bridge inverter and a center-tapped full-wave rectifier.](image)

1) LCC WITH TRAPEZOIDAL APPROXIMATION

Figure 3 shows operating waveforms for each operating mode of the LCC resonant converters for both CPS and HPS with trapezoidal approximation. The LCC resonant converter operates with two types of resonance. (a) A series resonance occurred by \(L_{r2}\) and \(C_{r2}\) and (b) a parallel resonance occurred by \(L_{r2}\) and \(C_{p2}\). To shape the resonant current as a trapezoid, the parallel resonant frequency (\(f_{p2}\), determined by \(L_{r2}, C_{r2}, \) and \(C_{p2}\)) much faster than the series resonant frequency (\(f_{s2}\), determined by \(L_{r2}\) and \(C_{r2}\)) is chosen. Therefore, the value of \(C_{p2}\) is much less than \(C_{r2}\). Operating modes and design of resonant parameters are briefly explained as follows.

- Mode 1

With switches S1 and S4 on, the input voltage (\(V_{in}\)) is applied to the resonant tank. Then, the resonant current (\(i_{L2}\)) rises until the voltage of \(C_{p2}\) is clamped by output voltage referred to the primary side of the transformer (\(V_{o,pr}\)). Since
the value of $C_{p2}$ is much less than $C_{c2}$, it can be assumed that the resonant frequency is almost equal to $f_{op2}$. During M1, no charge is transferred to a load.

- **Mode 2**

  The resonant current in M2 is maintained as a flat form due to (a) lower applied voltage ($V_{in} - V_{o,ps}$) to the resonant tank and (b) higher characteristic impedance than M1. Hence, the voltage of $C_{c2}$ ($V_{C2}$) linearly increases during M2. To minimize an effect of the voltage of the series resonant capacitor ($V_{Cl1}$) to the shape of the resonant current, the value of $C_{l1}$ is chosen to be enormously high.

- **Mode 3**

  After turning off S1 and S4, the resonant current still flows in the positive direction through the anti-parallel diodes of S2 and S3. Therefore, a large negative voltage is applied to the resonant tank, which results in the rapid decrease of the current. In addition, S2 and S3 are capable of soft-switching during M3 because their anti-parallel diodes are conducting. As the direction of the current changes, M4 starts. Analyses from M4 to M6 are the same as those from M1 to M3.

2) **DESIGN OF RESONANT PARAMETERS**

Resonant parameters must be designed in consideration of a change of load. Since $f_{op1}$ is relevant to a loaded quality factor, deciding this value affects the light load operating range as well as a peak value of the resonant current and the relation is shown in Fig. 4. In this paper, $f_{op2}$ is designed to be double the value of $f_{sw2}$, which makes power supplies cover 10% of the rated load operation at 3 times the switching frequency [46]. By referring to [46], a relationship between $I_{Lr2,peak}$, $f_{op2}$, and power coverage for the light load can be expressed as (1).

$$P_{TR} = \frac{1 - \frac{5}{8} \frac{f_{sw2}}{f_{op2}}}{f_{op2}} \cdot V_{in} \cdot I_{Lr2,peak}$$  (1)

Due to the assumption that $C_{c2}$ is much larger than $C_{p2}$, a characteristic impedance during M1 ($Z_{op2}$) can be approximated by just using $L_{r2}$ and $C_{p2}$. With the obtained value of $I_{Lr2,peak}$ in (1), $Z_{op2}$ is calculated as (2).

$$Z_{op2} = \sqrt{\frac{L_{r2}}{C_{p2}}} \cdot \frac{2 \cdot V_{in} + V_{C2,peak}}{I_{Lr2,peak}}$$  (2)

Values of $L_{r2}$ and $C_{p2}$ are derived by using the result from (3) and (4).

$$L_{r2} = \frac{Z_{op2}}{2 \cdot f_{op2}}$$  (3)

$$C_{p2} = \frac{L_{r2}}{Z_{op2}}$$  (4)

As aforementioned, the value of $C_{r2}$ can be chosen to be quite large value to make the resonant current during M2 flat. The value also can be derived as (5) by calculating $V_{C2,peak}$ for the exactly required output power.

$$C_{r2} = \frac{\left(\frac{T_{sw2}}{2} - \frac{3}{8} \cdot T_{op2}\right)}{2 \cdot V_{C2,peak}}$$  (5)
Calculated parameters are shown in Table II. PSpice simulation is conducted and waveforms of resonant current and resultant output voltage for each power supply are shown in Fig. 4. Waveforms of each resonant current follow the trapezoidal approximation.

At the same voltage (4.3kV) for the resistive load, the developed CPS achieved lower output voltage ripple (< 45V) than the one (< 85V) with a commercial magnetron power supply, SM445 from MKS [30], [31] as shown in Table III.

### III. STABILIZATION OF A COMMERCIAL MAGNETRON

#### A. FREE-RUNNING CHARACTERISTICS OF THE MAGNETRON DRIVEN BY THE POWER-SUPPLIES

A commercial S-band magnetron (National Electronics YJ1540) is driven by the developed power supplies. Figure 6 shows a waveform of the cathode voltage under free-running condition with a forward power of 1kW. The voltage ripple of CPS is 0.2%, which is better than the result predicted from the PSpice simulation. Since the operating voltage (4kV) driving the magnetron load is lower than the designed voltage (5kV), a higher switching frequency (650kHz) inversely proportional to the voltage contributes to the enhancement. The switching frequency of 650kHz is observed in Fig. 6 where the voltage ripples of 13 periods are monitored during 20us. Figure 7 shows magnetron spectrum under the free-running condition with DC heater, where the resolution bandwidth (RBW) and the video bandwidth (VBW) are set to 1kHz. A black line of Fig. 7 (b) is a spectrum from the magnetron (driven at the output power of 1kW) by the CPS with the heater off after warming up the cathode. When the heater is off (filament-off), the spectral purity of the magnetron is improved for short, but the temperature of the cathode becomes lower because of the cooling mechanisms and the output frequency becomes unstable in the long term for the CPS to compensate for the reduced emission current from the cooler cathode. A DC heater was introduced to stabilize the output frequency of the magnetron and minimize noise caused by the heater. The cathode is heated at 4V and 10.5A, then the heater power is reduced to 1V and 3A after the driving condition is stabilized (in a few minutes). Figure 7 (a) and (b) show the spectrum according to the heater power. The heater power was reduced from 42W to 3W, and the noise from the magnetron was reduced accordingly [50]. When the heater power is decreased to 3W, the linewidth is almost the same as the heater-off condition. A temperature of the magnetron filament with respect to the heater current is divided into two regions, (1) pre-heating (over-heating) region where the filament temperature increase as the filament current increase, and (2) self-heating region where the filament temperature maintains regardless of the heater current [51]. In the (1) pre-heating region, smoothing effect of anode current dominates the noise: The feedback system of the DC stabilized power supply is unstable to control the anode current because the
filament temperature is high enough for space charge limited operation, which results in the noise as a function of the anode current owing to the pushing effect [51].

In the (2) self-heating region, the back-bombardment energy of electrons is the main source of heating so that the filament temperature remains at a constant even without the filament current. The conduction cooling and/or the emission cooling accompany axial asymmetry of the filament temperature along the cathode axis, which results in the change of the circulating frequency of the electron spoke synchronized with the RF field by the $E \times H$ drift along the axis as discussed in [52], [53]. Non-uniform emission along the cathode may produce spurious noise, as experimentally demonstrated in the paper by applying cathode shield in [53]. The filament-off technique has a difficulty in maintaining the magnetron operation due to the excessive falloff of the filament temperature owing to cooling mechanisms. When the filament temperature is cooled down below the stable operation condition, the feedback system of the power supply is unstable to make up the anode current, which may attribute to the long-term drift of the phase of the magnetron in our previous study [28]. Therefore, in this study, the DC power supply is employed for the filament and optimize condition to compensate for the cooling of the filament. In Fig. 7(b), the lower the heater power moves from 12 W to 3 W, the narrower the linewidth at -50 dBc follows. The linewidth with the heater power of 3 W is comparable to the one when the heater is off.

**B. FURTHER STABILIZATION WITH A PLL INJECTION**

A PLL injection was applied to the magnetron driven by the developed CPS and HPS to demonstrate further improvements in frequency and phase control. The injection signal is generated from a signal generator (Keysight N5171B) and amplified by a power amplifier (KRF KAH2453-40TS-UNF), then fed into the magnetron through a three-port circulator terminated with a load.
The PLL mainly consists of a double-balanced mixer (Mini-Circuits SYM-25DLHW) detecting the phase difference between the reference signal and the sampled microwave from the magnetron, and the control circuit producing the voltage to adjust the phase of the phase shifter accordingly. The phase shifter (Analog Devices HMC928) in front of the balanced mixer is used to compensate the phase of the magnetron output [28].

Figure 8 shows spectral characteristics of the injection-locked magnetron with the PLL at the output of 1kW at the span of (a) 10MHz and (b) 100kHz, respectively, under the same measurement conditions. The spectral purity of the magnetron is improved to the extent of the linewidth at 60dBc less than 13kHz as depicted in Fig. 8 (b), which is comparable to the one of the reference signals itself injected through the PLL [54].

The phase of the magnetron is monitored by a phase detector (Analog Devices AD8302) with the sensitivity of 10mV/°. To minimize the effect of random thermal noises, the measured signals are averaged over ten times. Figure 9 shows the extreme phase-stability of around 0.2° peak to peak. When the free running case is compared with the PLL injection case, the spectral purity is dramatically improved through the PLL injection and various noise components of the magnetron is eliminated. Consequently, the negative voltage of the cathode extracting electrons becomes more stable than that of the free-running case as shown in Fig. 9.

Owing to the precise HPS-control, the long-term drift of the phase is stabilized as presented in Fig. 10, where the variation of the phase is further restricted within ±0.8° even without the averaging to filter out the effect of random thermal noises owing to DC HPS. Consequently, the cooling mechanisms of the magnetron are effectively compensated, and long-term stabilization of the phase is realized. Systematic fluctuation found in Fig. 10 is about 60Hz, which implies the signal from the magnetron driven by the power supplies is irrelevant because three-phase inputs of 380V AC provide the power to the supplies. The enhanced stability contributes to realizing a power-variable phase-controlled magnetron (PVPCM). Figure 11 demonstrates the stability of the phase during the variation of the magnetron output, where the power is adjusted by changing the beam current at a fixed voltage of the cathode.
(blue point) of the magnetron from approximately 700W to 1050W. The phase (magenta point) remains at a constant value while the output power is swept. Owing to the successful suppression of a long-term instability of the magnetron in cooperation with the well-stabilized driving power supply and the heater power supply minimizing the cooling effects, the performance of the magnetron is further stabilized and the feasibility of the magnetron is verified satisfying the main characteristics required as the unit source constituting a phase-arrayed power-transfer system.

IV. CONCLUSION

Long-term stabilization of the phase (peak to peak 0.2°) of an S-band magnetron for high-power (1kW) was achieved by the driving with the DC HPS to compensate the cooling effects of the heater, in cooperation with the PLL assisted injection harnessing the magnetron along with the high-voltage CPS developed using an LCC (Inductor-Capacitor-Capacitor) resonant converter. And eligibility for the unit source of a phase-arrayed power-transfer system is proven by varying the output power while maintaining the phase at a constant. Compact but powerful and efficient magnetrons became promising for advanced high-power microwave applications including a long-distance WPTS and replacement of the bulky klystrons for linear accelerators, by overcoming the inherent instability in frequency and phase.

REFERENCES

[1] J.M. Osepchuk, "The magnetron and the microwave oven: A unique and lasting relationship," 2010 International Conference on the Origins and Evolution of the Cavity Magnetron, pp. 19-20.
[2] J. Li, Z. Yao, L. Ye, and P. Guan, "Design of Magnetron Transmitter for Doppler Weather Radar," 2019 International Conference on Meteorology Observations (ICMO), pp. 28-31.
[3] J.N. Burghartz, "Vacuum Device Applications," Guide to State-of-the-Art Electron Devices, Wiley (2013).
[4] H. Zhang, R. Yang, Y. He, A. Foudazi, L. Cheng, and G. Tian, "A Review of Microwave Thermography Nondestructive Testing and Evaluation," Sensors, vol. 17, no. 5, p.1123 (2017).
[5] S. Dbrowska, T. Chudoba, W. Tadeusz, K. Jacek, W. Lojkowski, "Current Trends in the Development of Microwave Reactors for the Synthesis of Nanomaterials in Laboratories and Industries: A Review," Crystals, vol. 8, no. 10, p. 379 (2018).
[6] W.C. Brown, "Satellite power system (SPS) magnetron tube assessment study (1981)" National Aeronautics and Space Administration, Scientific and Technical Information Branch.
[7] P.E. Glaser et al., "Feasibility Study of a Satellite Solar Power Station," NASA Contractor Report CR-2357.
[8] P.E. Glaser, "Power from the Sun: Its Future," Science, vol. 162, no. 3856, 857 (1968).
[9] W. C. Brown, "Beamed Microwave Power Transmission and its Application to Space," IEEE Transactions on Microwave Theory and Techniques, vol. 40, no. 6, 1239 (1992).
[10] W. Johnson, K. Dahlgburg, B. Bartolo, W. Dorsey, D. Gubser, P. Jenkins, N. Smith, W. Boneyck, M. Brown, D. Huber and P. Jaffe, "Space-based Solar Power : Possible Defense Applications and Opportunities for NRL Contributions," (2009).
[11] N. Shinohara, "Applications of WPT," Wireless Power Transfer via Radiowaves, Wiley (2014).
[12] E. Ackerman, "Japanese Demos Power Wireless Transmission for Space-Based Solar Farms," IEEE Spectrum (Mar. 2015).
[13] S. Sasaki, K. Tanaka, and K. Maki, "Microwave Power Transmission Technologies for Solar Power Satellites," Proceedings of IEEE, vol. 101, no.6, 1438 (June 2013).
[14] P. Jaffe, and J. McSpadden, "Energy Conversion and Transmission Modules for Space Solar Power," Proc. IEEE, vol. 101, no. 6, 1424 (2013).
[15] B. Strassner, and K. Chang, "Microwave Power Transmission: Historical Milestones and System Components," Proc. IEEE, vol. 101, no. 6, 1379 (2013).
[16] N. Shinohara and H. Matsumoto, "Research on Magnetron Phased Array with Mutual Injection Locking for Space Solar Power Satellite/Station," Electrical Engineering in Japan, vol. 173, no. 2, p.21 (2010).
[17] A. Massa, G. Oliveri, F. Viani and P. Rocca, "Array Designs for Long-Distance Wireless Power Transmission: State-of-the-Art and Innovative Solutions,"Proc. IEEE, vol. 101, no. 6, pp. 1464-1481 (2013).
[18] N. Shinohara, "Beam Control Technologies with a High-Efficiency Phased Array for Microwave Power Transmission in Japan," Proceedings of IEEE, vol. 101, no.6, 1448 (June 2013).
[19] B. Yang, T. Mitani, and N. Shinohara, "Experimental Study on a 5.8 GHz Power-Variable Phase-Controlled Magnetron", IEICE Transactions on Electronics, vol. E100-C, no. 10, 901- (2017).
[20] B. Yang, X. Chen, J. Chu, T. Mitani and N. Shinohara, "A 5.8-GHz Phased Array System Using Power-Variable Phase-Controlled Magnetrons for Wireless Power Transfer," IEEE Trans. Microw. Theory Techn., vol. 68, no. 11, 4951 (2020).
[21] M.H. Yoon, S.J. Park, E.S. Kim, W.H. Hwang, and D.E. Kim, "Accelerating Device for Next Generation Radiation (in Korean)," Physics and High Technology, vol. 18, pp. 6-19 (2009).
[22] H. Wang, T. Plawski, R.A. Rimmer, "Simulation Study using an Injection Phase-Locked Magnetron as an Alternative Source for SRF Accelerators, " 6th Int'l Particle Accelerator Conference (2015).
[23] R.L. Bell, "Klystron oscillator noise theory," Br. J. Appl. Phys. 7, 262, 1956.
[24] O. Dunbrabij and G. S. Nusinovich, "Effect of technical noise on radiation linewidth in free-running gyrotron oscillators," Plasmas vol. 4, no. 5, pp. 14131723 (1997).
[25] L.V. Lubyak, N.K. Skalyga, and A.N. Kutfin, "Noise spectrum of the 140-GHz gyrotron designed for controlled thermoelectric fusion installations," Tech. Phys. 54, 1332 (2009).
[26] S.T. Han, R.G. Griffin, K.Nian Hu, C.G. Joo et al., "Spectral Characteristics of a 140-GHz Long-Pulsed Gyrotron," IEEE Trans. Plasma Sci., vol.35, no. 3, pp. 559-564 (2007).
[27] T. Idehara, S.P. Sabelchikov, M. Glyavin, S. Mitsudo, "The Gyrotrodes as Promising Radiation Sources for THz Sensing and Imaging," Appl. Sci. 10, 980 (2020).
[28] S.T. Han, D.K. Kim, J.S. Kim, and J.R. Yang, "Noise Suppression and Precise Phase Control of a Commercial S-Band Magnetron," IEEE Access vol. 8, 145881 (2020).
[29] C.R. Smith, C.M. Armstrong and J. Duthie, "The microwave power module: a versatile RF building block for high-power transmitters," Proc. IEEE, vol. 87, no. 5, pp. 717-737 (1999).
[30] 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, no. 7, 1721 (2006).
[31] I. Tahir, "Frequency and Phase Locking of a CW Magnetron: with a Digital Phase Locked Loop Using Pushing Characteristics," Doctoral Dissertation, Lancaster University (2008).
[32] Z. Liu, X. Chen, M. Yang, K. Huang, and C. Liu, "Experimental Studies on a 1-kW High-Gain S-Band Magnetron Amplifier With Output Phase Control Based on Load-Pull Characterization," IEEE Trans. Plasma Sci., vol. 46, no. 4, 909 (2018).
[33] F.M. Charbonnier, R.W. Strayer, L.W. Swanson, and E.E. Martin, "Nottingham Effect in Field and T-F Emission: Heating and Cooling Domains, and Inversion Temperature," Phys. Rev. Lett. 13, 397 (1964).
[34] T. Durakiewicz and S. Halas, "Cooling of an incandescent filament by thermionic emission," Int. J. Mass Spectrom., 177, 155 (1998).
[35] Yoshikazu Hishinuma, Theodore H. Geballe, and Boris Y. Moyzhes, "Measurements of cooling by room-temperature thermionic emission across a nanometer gap," J. Appl. Phys. 94, 4690 (2003).
[36] L. Wu and L. K. Ang, "Low temperature refrigeration by electron emission in a crossed-field gap," Appl. Phys. Lett. 89, 133503 (2006)
[37] L. Wu and L. K. Ang, "Low temperature refrigeration by using thermal-field electron emission in a coaxial cylindrical diode," J. Appl. Phys. 104, 084506 (2008)
[38] T.L. Westover and T.S. Fisher, "Simulation of refrigeration by electron emission across nanometer-scale gaps," Phys. Rev. B 77, 115426 (2008)
[39] A. Yangui, M. Besccond, T. Yan, et al., "Evaporative electron cooling in asymmetric double barrier semiconductor heterostructures," Nat. Commun. 10, 4504 (2019)
[40] V. R. Vakacharla and A. K. Rathore, "Analysis and Design of Current-Fed Three-Phase-Isolated LCC-T Resonant Converter for Low-Voltage High-Current Applications," in IEEE Trans. Ind. Appl., vol. 55, no. 6, pp. 6527-6537, Nov.-Dec. 2019
[41] T. Konjedic, L. Korosec, M. Truntic, C. Restrepo, M. Rodič and M. Milanović, "DCM-Based Zero-Voltage Switching Control of a Bidirectional DC–DC Converter With Variable Switching Frequency," in IEEE Trans. Power Electron., vol. 31, no. 4, pp. 3273-3288, April 2016
[42] Y. Wei, Q. Luo and A. Mantooth, "Comprehensive analysis and design of LLC resonant converter with magnetic control," in CPSS Trans. Power Electron. and Applications, vol. 4, no. 4, pp. 265-275, Dec. 2019
[43] R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies," in IEEE Trans. Power Electron., vol. 3, no. 2, pp. 174-182, April 1988
[44] J. Zheng, S. Lu and J. Li, "LLC and LCC Analysis and Comparison of Resonant Converters," 2020 35th Youth Academic Annual Conference of Chinese Association of Automation (YAC), 2020, pp. 226-231 [R1]
[45] J. Kim, C. Kim, J. Kim and G. Moon, "Analysis for LLC resonant converter considering parasitic components at very light load condition," 8th International Conference on Power Electronics - ECCE Asia, 2011, pp. 1863-1868 [R2]
[46] S. Jang, C. Yu and H. Ryoo, "Trapezoidal Approximation of LCC Resonant Converter and Design of a Multistage Capacitor Charger for a Solid-State Marx Modulator," in IEEE Trans. on Power Electron., vol. 33, no. 5, pp. 3816-3825, May 2018
[47] J. Bae, J. Kim, H. Kim, C. Yu and S. Jang, "Modular Design of a Bipolar-Pulse-Power-Supply-Based LCC Resonant Converter for Strategic Mineral Exploration," in IEEE Trans. Ind. Electron., vol. 66, no. 9, pp. 6846-6855, Sept. 2019
[48] M. Nakaoka, B. Saha, H. Sugimura, S. P. Mun, E. Hiraki and H. Omori, "Direct High Frequency Soft Switching Inverter Type AC-DC Power Converter with Boost Function for Consumer Magnetron Drive," IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society, 2007, pp. 1336-1341 [R3]
[49] S. Jang, H. Ryoo, S. Ahn, J. Kim and G. H. Kim, "Development and Optimization of High-Voltage Power Supply System for Industrial Magnetron," in IEEE Transactions on Industrial Electronics, vol. 59, no. 3, pp. 1453-1461, March 2012 [R4]
[50] I. Tahir, A. Drexler, and R. Carter, "Noise Performance of Frequency- and Phase-Locked CW Magnitrons Operated as Current-Controlled Oscillators," IEEE Transactions on Electron Devices, vol. 52, no. 9, pp. 2096-2103, Sep. 2005
[51] T. Mittani, N. Shinohara, H. Matsumoto, M. Aiga, N. Kuwahara, "Experimental research on noise reduction of magnetrons for solar power station/satellite," in IEEE Asia-Pacific Radio Sci. Conf., Qingdao, China, Aug. 2004, pp. 603-606
[52] K. Yamamoto, H. Kurokuma, T. Koinuma, "A Study of Magnetron Noise," IEEE Transactions on Electron Devices, vol. ED-34, no. 5, pp.1223-1226, May 1987
[53] T. Mittani, N. Shinohara, H. Matsumoto, M. Aiga, N. Kuwahara, and T. Ishii, "Noise-Reduction Effects of Oven Magnetron With Cathode Shield on High-Voltage Input Side," IEEE Transactions on Electron Devices, vol. 53, no. 8, pp. 1929-1936, Aug. 2006
[54] KEYSIGHT TECHNOLOGIES "EXG X-Series Signal Generators N5171B Analog & N5172B Vector," in KEYSIGHT Date Sheet, Oct. 2020. [Online]. Available: https://www.keysight.com/
fabricated folded waveguide TWT operating at Ka-band. He was a Researcher in the research institute of basic science, SNU, in 2005, where his research focused on novel vacuum electron devices employing recent innovations, such as photonic crystal and cold cathode based on nano/MEMS technologies. In September 2005, he joined the Plasma Science and Fusion Center, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, as a Post-Doctoral Research Associate, where he worked on sub-THz gyrotrons (140 and 460 GHz) for DNP/NMR research and measurement of extremely loss in the components of the 170-GHz ITER ECH transmission-line. Since 2008, he has been a Senior and Principal Researcher with the Korea Electrotechnology Research Institute (KERI), Changwon, South Korea, where he led projects to develop a 0.2/0.4THz gyrotron for real-time inspection of foreign objects in food. By integrating the core competencies with KERI, such as super-conducting magnets and high-voltage power-supplies, he built a 100 kW level W-band gyrotron as a prototype for civilian active denial system, a humanitarian non-lethal weapon for the first time in Korea. He currently serves as the Director of the Electrophysic Research Center with KERI and the Professor with the Department of Energy and Power Conversion Engineering, University of Science and Technology, Daejeon, South Korea. His research interest covers high-power microwaves and charged particles and their applications for advanced industry and science.