

A 2.4 GHz-Band 100 W GaN-HEMT High-Efficiency Power Amplifier for Microwave Heating

Keigo Nakatani · Toshio Ishizaki*

Abstract

The magnetron, a vacuum tube, is currently the usual high-power microwave power source used for microwave heating. However, the oscillating frequency and output power are unstable and noisy due to the low quality of the high-voltage power supply and low Q of the oscillation circuit. A heating system with enhanced reliability and the capability for control of chemical reactions is desired, because microwave absorption efficiency differs greatly depending on the object being heated. Recent studies on microwave high-efficiency power amplifiers have used harmonic processing techniques, such as class-F and inverse class-F. The present study describes a high-efficiency 100 W GaN-HEMT amplifier that uses a harmonic processing technique that shapes the current and voltage waveforms to improve efficiency. The fabricated GaN power amplifier obtained an output power of 50.4 dBm, a drain efficiency of 72.9%, and a power added efficiency (PAE) of 64.0% at 2.45 GHz for continuous wave operation. A prototype microwave heating system was also developed using this GaN power amplifier. Microwaves totaling 400 W are fed from patch antennas mounted on the top and bottom of the microwave chamber. Preliminary heating experiments with this system have just been initiated.

Key Words: GaN-HEMT, High Power Amplifier, High Efficiency, Harmonic Processing Technique, Microwave Heating.

I. INTRODUCTION

The objective of this research is the realization of a high-efficiency microwave heating system that uses a solid-state amplifier. The magnetron, which is a vacuum tube, is commonly used as a signal source in conventional microwave chemical reaction systems. The magnetron shows high efficiency at high output power, but its oscillating frequency and the output power are unstable, which leads to poor reliability for chemical reactions. The output power from a magnetron is conducted to the chemical chamber through a waveguide, but this does not necessarily lead to full power utilization. The actual absorption efficiency greatly depends on the material properties of the object being heated. A low absorption

efficiency results in most of the power (e.g., more than half) being reflected to the magnetron and dissipated as heat.

This study presents a new technique to improve absorption efficiency by frequency and phase control. In addition, power from multiple antennas is combined by controlling the phase in the heating furnace. This is the largest advantage of a solid-state heating system, because a magnetron cannot control either the oscillation frequency or the phase of the output signal. The proposed system can control the frequency and phase with high accuracy through the use of a semiconductor device.

The high power amplifier (HPA) that uses the emerging technology of a GaN-HEMT (Gallium Nitride High Electron Mobility Transistor) can provide a high output power

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Department of Science and Engineering, Ryukoku University, Shiga, Japan.

*Corresponding Author: Toshio Ishizaki (e-mail: ishizaki@rins.ryukoku.ac.jp)

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comparable to that of a magnetron. Current HPAs include the L-band 500 W [1] and S-band 800 W [2], but HPAs with output powers of more than 100 W have been reported even in the high frequency bands (C-, X- and Ku-bands) [3, 4]. A power added efficiency (PAE) of 80% is achieved for output power of 16.5 W [5]. However, the efficiency of GaN-HEMT is somewhat lower than that of a magnetron for the condition of high output power with CW operation.

In recent years, harmonic processing techniques have been extensively studied in order to design high efficiency power amplifiers. Ideally, an efficiency of 100% can be obtained by a harmonic processing technique, such as class-F and inverse class-F, where the load impedances for harmonics are controlled as zero or infinity. However, the effects of parasitic elements in GaN-HEMT cause the optimum load impedances to deviate from the ideal impedances [6], thereby deteriorating the efficiency. This could be restored by optimizing the reflection phase of the harmonics, and past research has reported the use of field effect transistors (FETs) with internal or on-chip matching circuits [7, 8]. However, a high efficiency power amplifier using a packaged external matching transistor has not yet been reported.

The present study describes the design of a 100-W GaN-HEMT HPA that uses a large-signal model of a transistor and considers the reflection phases of the harmonics. The intention of the design is to incorporate the HPA into a microwave heating system.

The solid-state microwave heating system is constructed by designing and fabricating a 200-W power amplifier module. The developed heating system has a total of 400 W output power fed from two metal patch antennas installed on the top and bottom of the chamber. The frequency and phase in this system can be controlled electronically to realize high-efficiency heating. Reflected power in the chamber is detected by a monitoring sensor in real time. This paper demonstrates the advantages of the solid-state microwave heating system, where the heating efficiency depends on frequency and phase.

II. LARGE SIGNAL SIMULATION OF GAN-HEMT

The GaN-HEMT used in this study is a CGH40120F, which is a GaN on SiC device manufactured by Cree. Fig. 1 shows the characteristics of the source pull (SP) and load pull (LP) for a fundamental frequency wave, using a large-signal model provided by Cree. Advanced Design System (by Keysight) is used in circuit simulation. The non-linear simulation yields an output power (P_{out}) of 50.1 dBm, associated gain of 10.7 dB, and PAE of 65.7% under conditions of a frequency of 2.45 GHz, V_{ds} of 28 V, I_{ds} of 1.0 A, and input power (P_{in}) of 40 dBm. Consideration of the fun-

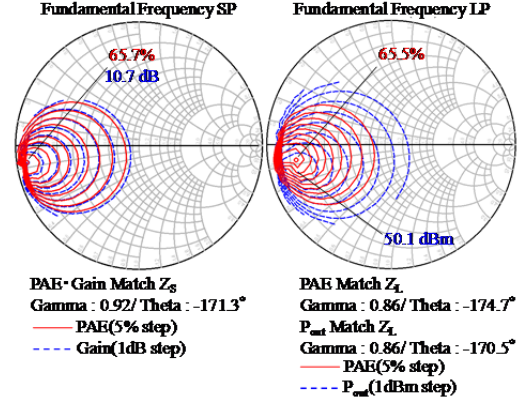


Fig. 1. SP · LP contours for the fundamental frequency. SP=source pull, LP=load pull, PAE=power added efficiency.

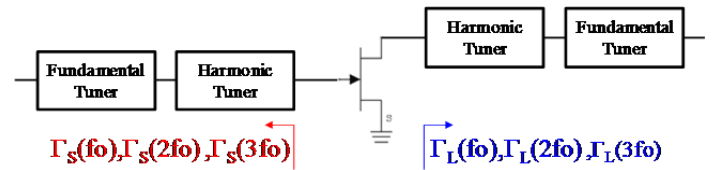


Fig. 2. Setup for harmonic load-pull and source-pull.

damental wave only gives a relatively low PAE of about 65%. Thus, improvement of efficiency is attempted by adjusting the harmonic reflections.

Fig. 2 shows a setup for simulation and measurement of harmonic load-pull and source-pull. This is often performed using a mechanical tuner (for example, the Focus microwave PHT tuner etc.), but this research calculates the dependencies of PAE on the reflection phases of the second and third harmonics by a load-pull simulation. Figs. 3 and 4 show that PAE is improved by 10% near the reflection phase of 170° for the 2nd harmonic, while the improvement for the 3rd harmonic is small. Thus, the reflection phase of 3rd harmonic

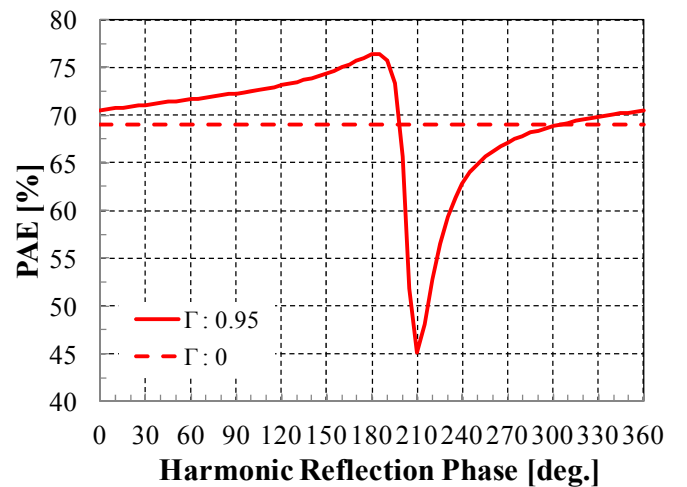


Fig. 3. Power added efficiency (PAE) variation for the reflection phase of the 2nd harmonic.

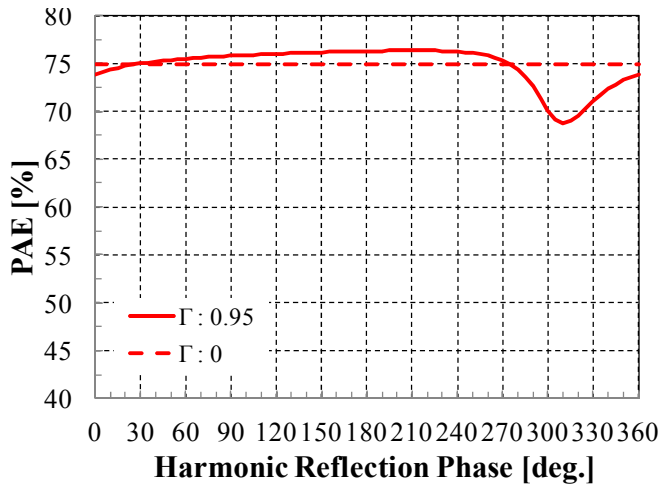


Fig. 4. Power added efficiency (PAE) variation for the reflection phase of the 3rd harmonic.

Table 1. Simulated optimum impedances

	Magnitude	Phase[deg.]
Fundamental at load side $\Gamma_L(f_0)$	0.91	-176
2 nd Harmonic at load side $\Gamma_L(2f_0)$	0.95	170
3 rd Harmonic at load side $\Gamma_L(3f_0)$	0.95	210
Fundamental at source side $\Gamma_s(f_0)$	0.97	-170

is set to the angle, at which the efficiency is not deeply degraded. The optimum impedances, including the fundamental wave, are listed in Table 1.

III. DESIGN OF POWER AMPLIFIER

A schematic of the amplifier circuit is shown in Fig. 5. The harmonic reflection circuit is connected to the drain of the transistor. The harmonics at the gate side have little effect on efficiency. Thus, input matching is considered only for the fundamental frequency. The designed circuit and pattern for harmonic reflection are shown in Fig. 6.

In Fig. 6(a), the open stubs (Stub1, Stub2) of the quarter-

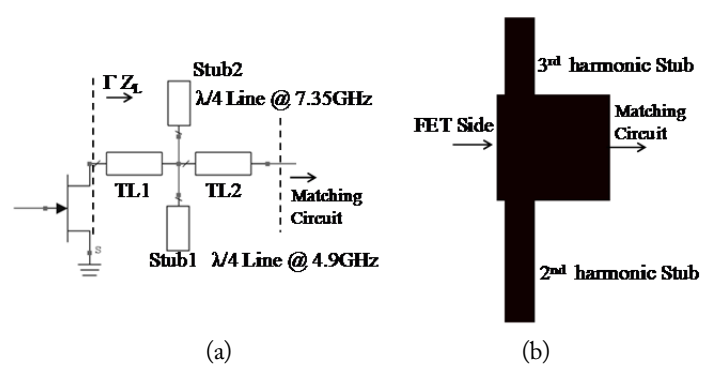


Fig. 6. Circuit schematic of the harmonic reflection circuit: (a) schematic and (b) circuit pattern.

wavelength for each harmonic are used for harmonic processing. The reflection phase is controlled by the length of the transmission line TL1. The widths of TL1 and TL2 are set to 7 mm based on the electrode terminal size of the FET; this corresponds to a characteristic impedance of 17.7 Ω. The reflection phase of the second harmonic is mainly determined by TL1 and is set to the optimal value of 2.59°, in terms of the fundamental wave. Fortunately, this length was not a length where the reflection phase of third harmonic degrades the efficiency. If changes are desired in the reflection phase of third harmonic, the connection points for the second and third harmonics should be separated. The impedance for the fundamental wave is controlled by the length of TL2 and the capacitor (C2). The length of TL2 is set to 54.6°, and C2 is set to 1.1 pF.

Fig. 6(b) shows a pattern designed by electromagnetic field analysis, corresponding to circuit analysis. Its reflection characteristics and transmission characteristics are shown in Fig. 7(a) and (b). The respective impedances (Γ_L , $\Gamma_L(2f_0)$, $\Gamma_L(3f_0)$) are confirmed to agree well with the target impedances and that the harmonics are sufficiently suppressed or reflected. The transmissions of the harmonic signal are only -28.6 dB at 4.9 GHz and -33.2 dB at 7.35 GHz. The input and output circuits of the amplifier are fabricated on a MEGTRON6 R-5775N made by Panasonic and an RT/duroid 6035HTC by Rogers, respectively.

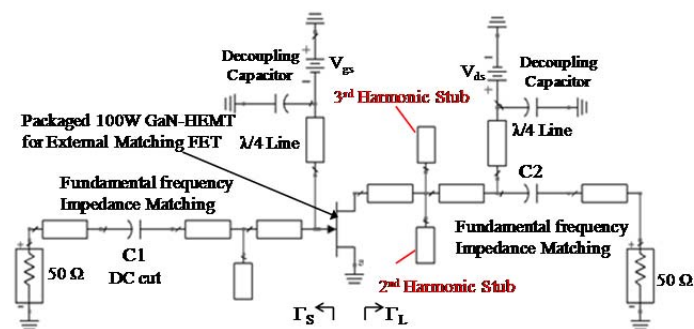


Fig. 5. Circuit schematic of the designed amplifier.

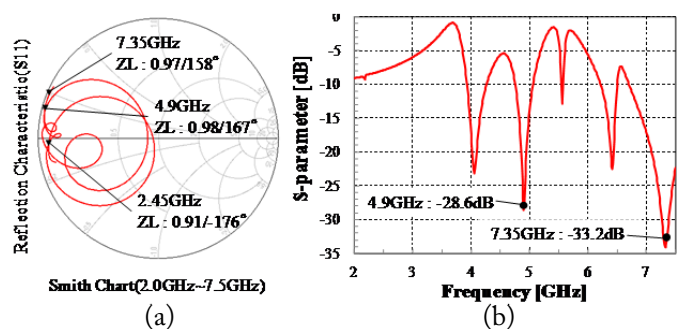


Fig. 7. Characteristics of the output circuit: (a) reflection characteristics (S_{11}) and (b) transmission characteristics (S_{21}).

IV. MEASURED CHARACTERISTICS OF THE AMPLIFIER

A photograph of a prototype 100 W GaN HPA is shown in Fig. 8. The simulation was carried out using the non-linear large signal model provided by Cree. The simulated and measured input-output small-signal characteristics and large-signal characteristics are shown in Figs. 9 and 10. The bias conditions of the amplifier are V_{ds} of 30 V, V_{gs} of -2.73 V and I_{ds} of 1.0 A. The solid lines in Fig. 9 indicate the measured values and dashed lines indicate the simulated values. The measured linear gain of 14.6 dB shows very good agreement with the simulated value at 2.45 GHz. The dotted lines in Fig. 10 indicate the measured values and the dashed lines indicate simulated values. A saturated output power of 50.4 dBm, associated gain of 9.2 dB, drain efficiency of 72.9%, and PAE of 64% were obtained. The measured efficiencies were slightly lower than those of the simulated values. This difference might be due to a larger loss in the output circuit than in the simulation and to insufficient accuracy of the simulation model. However, the achieved efficiency is the highest for an amplifier using an external matching FET, to the best of our knowledge, with the exceptions of [7, 8], which used internal matching or on-chip matching.

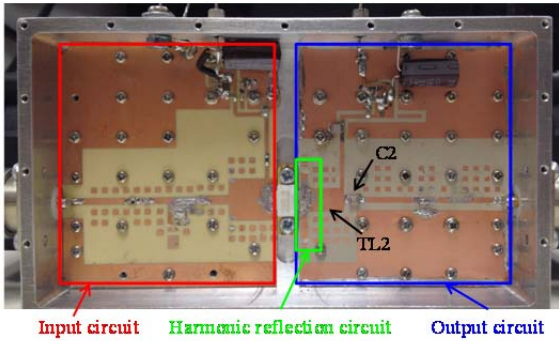


Fig. 8. Photograph of 2.45 GHz 100 W GaN-HEMT high power amplifier.

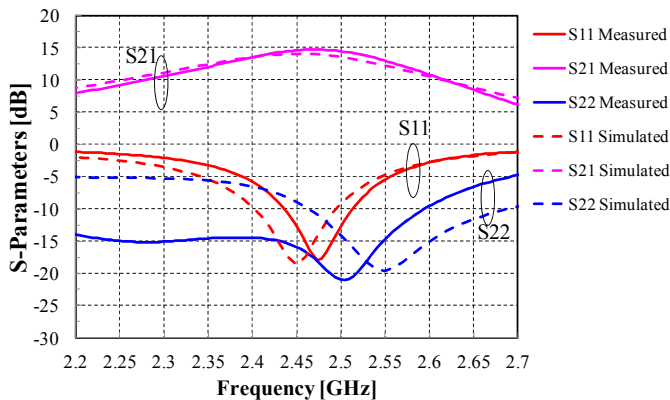


Fig. 9. Measured and simulated small-signal characteristics.

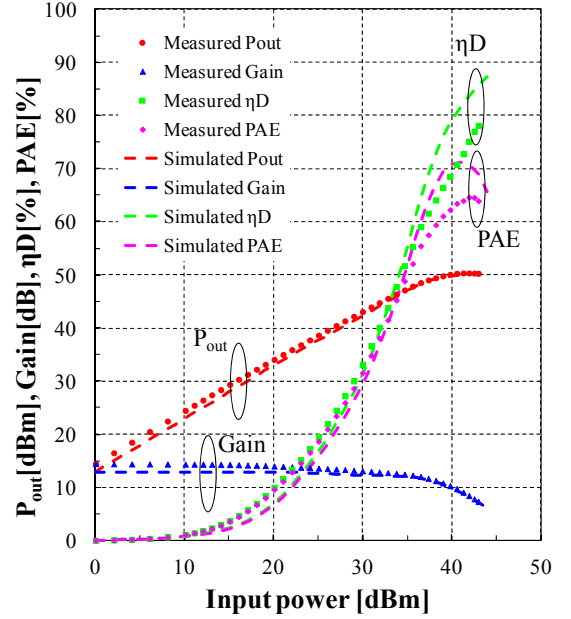


Fig. 10. Measured and simulated large-signal characteristics. PAE = power added efficiency.

Fig. 11 shows the simulated and measured dependences of the output power and PAE on the drain voltage. The output power increases according to the drain voltage, but the efficiency is saturated and does not show further increases. An output power over 100 W is obtained at drain voltages higher than 28 V. An output power of 120 W was obtained, but the PAE was degraded to 62% so the reliability of the device might not be guaranteed. Fig. 12 shows the simulated and measured dependences of the output power and PAE on frequency. The measured output power is relatively higher and the efficiency is lower than for the simulation, so the impedance of the prototype circuit is more likely matched with the high power condition. Thus, PAE could be improved by modifying the load impedance, which deviated from the high efficiency condition.

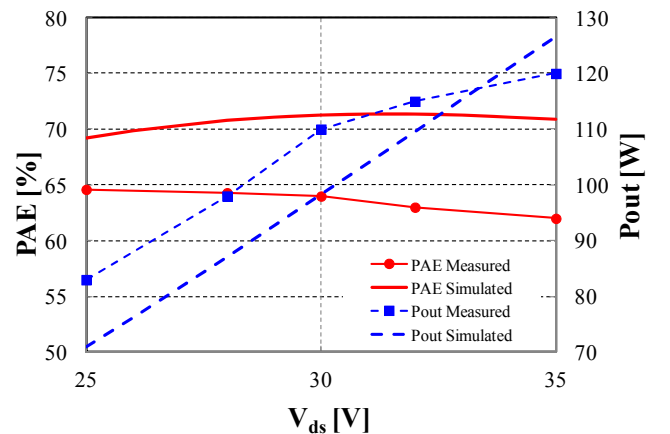


Fig. 11. Dependences of P_{out} and PAE on drain voltage. PAE = power added efficiency.

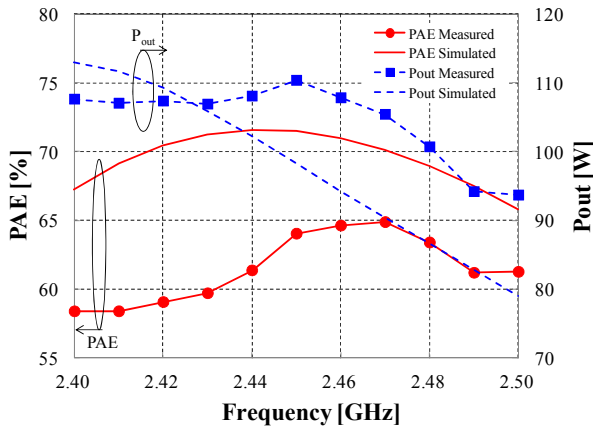


Fig. 12. Frequency dependence of P_{out} and power added efficiency (PAE).

V. SYSTEM DESIGN OF THE MICROWAVE HEATING SYSTEM

A microwave heating system was constructed using the developed amplifier. The heating system comprised two 200 W GaN HPA modules, in which the 100 W GaN HPAs are combined by Wilkinson combiners. Thus, the total maximum output power is 400 W, fed from two patch antennas mounted on the top and bottom of the heating chamber. Fig. 13 shows the prototype 200 W GaN HPA module. The size of the 200-W module is 180 mm by 120 mm; miniaturization has not yet been considered.

Fig. 14 shows the structure of the patch antenna for high power handling. The antenna has a metal-air structure, comprising a circular aluminum plate and a center conductor pin connected to the plate at its impedance matching point. This structure can handle up to a few hundred Watts. Fig. 15 shows the simulated and measured performances of the patch antenna in free space. The EMPro (by Keysight) is used for 3D electromagnetic field analysis; this antenna has relatively wide-band characteristics. The gain of the antenna is about 5 dB higher than that of a conventional patch antenna.

Fig. 16 shows a block diagram of the developed GaN mi-

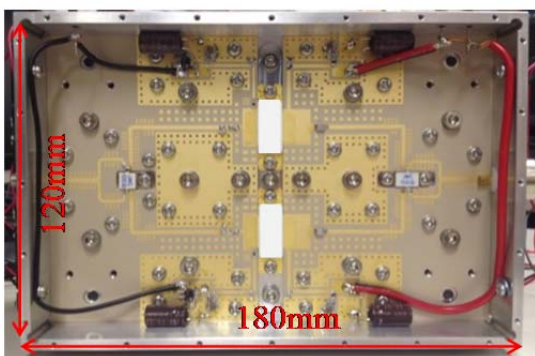


Fig. 13. Photograph of 2.45 GHz 200 W GaN high power amplifier module.

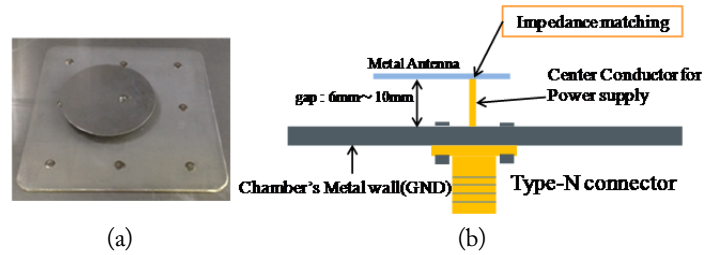


Fig. 14. Photograph of the metal patch antenna. (a) Prototype antenna and (b) structure of antenna.

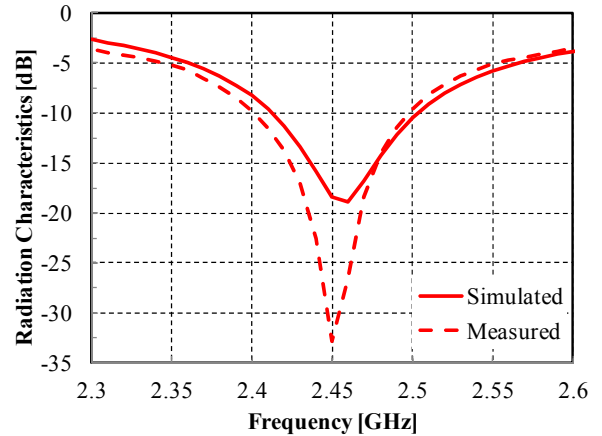


Fig. 15. Radiation characteristic of the metal patch antenna.

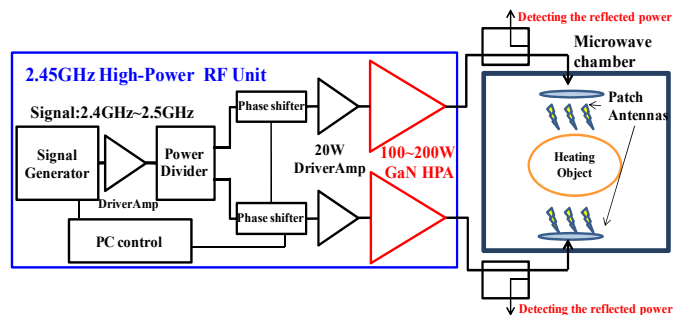


Fig. 16. Block diagram of GaN microwave heating system.

crowave heating system. The system consists of a signal generator, a power divider, variable phase shifters, variable attenuators, driver amplifiers, GaN HPAs, patch antennas, a heating chamber, reflected power sensors, and a control PC. The signal generator, variable phase shifters, and variable attenuators can be controlled electronically from the PC via USB connections. Fig. 17 shows a photograph of the constructed system.

At present, basic heating experiments have just been initiated and 100 mL of water in glass cup was successfully heated. The temperature of the water rose from 20°C to over 90°C in 90 seconds. An experiment to study chemical reactions was also carried out in which silver nano-particles were produced from an oxide solution by microwave heating.

Development of control software is underway. The experiments presented here were conducted manually, but a fully-



Fig. 17. The experimental microwave heating system.

automatic heating system will be constructed soon. The completed version of the system will allow automatic detection of the change in absorption efficiency.

The frequency and phase are then controlled by the control PC according to a predetermined algorithm. This type of operation is difficult for a magnetron. Thus, the authors believe that the GaN microwave heating system is very effective and represents a promising new technology.

VI. CONCLUSION

A 2.45 GHz 100 W GaN-HEMT HPA with PAE of 64% was successfully designed and fabricated. Some difficulties encountered with high-power amplifiers, such as performance degradations due to parasitic elements, were overcome. The reflection phases of the harmonics were optimized by a precise design that used the large signal model of a GaN-HEMT. A prototype of a GaN microwave heating system was also developed. The total maximum output power was 400 W, which was fed from two patch antennas mounted on the top and bottom of the heating chamber. The frequency and phase can be controlled electronically to maximize absorption. The authors have initiated heating experiments and expect that this GaN microwave heating system could drastically improve the quality and productivity of chemical reactions. Therefore, this technology could reform the industry.

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REFERENCES

- [1] A. Maekawa, T. Yamamoto, E. Mitani, and S. Sano, "A 500 W push-pull AlGaIn/GaN HEMT amplifier for L-band high power application," in *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, San Francisco, CA, 2006, pp. 722–725.
- [2] E. Mitani, M. Aojima, A. Maekawa, and S. Sano, "An 800-W AlGaIn/GaN HEMT for S-band high-power application," in *Proceedings of CS Mantech Conference*, Austin, TX, 2007, pp. 213–216.
- [3] H. Maehara, H. Uchida, N. Kosaka, E. Kuwata, K. Yamanaka, J. Nishihara, K. Kawashima, and M. Nakayama, "Internally matched GaN FET at C-band with 220W output power and 56% power added efficiency," in *2012 Asia-Pacific Microwave Conference Proceedings (APMC)*, Kaohsiung, China, 2012, pp. 358–360.
- [4] H. Noto, H. Maehara, H. Uchida, M. Koyanagi, H. Utsumi, J. Nishihara, H. Otsuka, K. Yamanaka, M. Nakayama, and Y. Hirano, "X- and Ku-band internally matched GaN amplifiers with more than 100W output power," in *Proceedings of the 7th European Microwave Integrated Circuits Conference (EuMIC)*, Amsterdam, 2012, pp. 695–698.
- [5] D. Schmelzer and S. I. Long, "A GaN HEMT class F amplifier at 2 GHz with > 80% PAE," *IEEE Journal of Solid-State Circuits*, vol. 42, no. 10, pp. 2130–2136, 2007.
- [6] K. Yamanaka, Y. Tuyama, H. Ohtsuka, S. Chaki, M. Nakayama, and Y. Hirano, "Internally-matched GaN HEMT high efficiency power amplifier for space solar power stations," in *2010 Asia-Pacific Microwave Conference Proceedings (APMC)*, Yokohama, Japan, 2010, pp. 119–122.
- [7] K. Motoi, K. Matsunaga, S. Yamanouchi, K. Kunihiro, and M. Fukaiishi, "A 72% PAE, 95-W, single-chip GaN FET S-band inverse Class-F power amplifier with a harmonic resonant circuit," in *Proceedings of 2012 IEEE MTT-S International Microwave Symposium Digest*, Montreal, Canada, 2012, pp. 1–3.
- [8] N. Ui and S. Sano, "A 100W class-E GaN HEMT with 75% drain efficiency at 2GHz," in *Proceedings of the 1st European Microwave Integrated Circuits Conference*, Manchester, UK, 2006, pp. 72–74.

Keigo Nakatani



was born in Hyogo, Japan, on Dec. 17, 1990. He received the B.S. degree in the Department of Science and Engineering from Ryukoku University, Shiga, Japan, in 2013, and is currently working toward the M.S. degree in Department of Science and Engineering of Ryukoku University. His research interests include GaN high efficiency and high power amplifiers and high efficiency microwave heating systems using semiconductors. Mr. Nakatani is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan. In 2013, he was awarded the IEEE MTT-S Kansai Chapter Best Young Presentation Award.

Toshio Ishizaki



was born in Kagawa, Japan, on May 24, 1958. He received the B.S., M.S., and doctorate of engineering degrees from Kyoto University, Kyoto, Japan, in 1981, 1983, and 1998, respectively. In 1983, he joined Panasonic Corporation (former Matsushita Electric Industrial Company Ltd.), Osaka, Japan, where he has been involved in research and development on microwave circuitry and components, especially on microwave dielectric filters and power amplifiers for cellular radio communications. From 2004 to 2007, he worked for Matsushita Electronic Components Company Ltd., an affiliated company, as a director of the R&D laboratory. In 2010, he became a professor at Ryukoku University, and this is his current title. He received the 1998 OHM Technology Award from the Promotion Foundation for Electrical Science and Engineering, Japan. He also received the 2003 best paper award from IEEJ, Japan, in 2003. His current research subjects are in the area of wireless power transfer systems, microwave meta-material devices, LTCC filters, and high-efficiency power amplifiers. Dr. Ishizaki is a senior member of IEEE and a senior member of IEICE. He is now serving as chair of the IEEE MTT-S Kansai Chapter.