IEICE TRANSACTIONS

on Electronics

DOI:10.1587/transele.2024MMI0004

Publicized:2024/04/09

A PUBLICATION OF THE ELECTRONICS SOCIETY

The Institute of Electronics, Information and Communication Engineers
Kikai-Shinko-Kaikan Bldg., 5-8, Shibakoen 3chome, Minato-ku, TOKYO, 105-0011 JAPAN

Invited Paper

GaN Solid State Power Amplifiers for Microwave Power Transfer and Microwave Heating

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SUMMARY GaN solid state power amplifiers (SSPA) for wireless power transfer and microwave heating have been reviewed. For wireless power transfer, 9W output power with 79% power added efficiency at 5.8GHz has been achieved. For microwave heating, 450W output power with 70% drain efficiency at 2.45GHz has been achieved. Microwave power concentration and uniform microwave heating by phase control of multiple SSPAs are demonstrated.

key words: solid state power amplifier, microwave power transfer, microwave heating, phase control, carbon neutral, harmonic termination

1. Introduction

GaN devices have become the main player for the 5th generation mobile communication (5G) base transceiver stations [1] and infrastructure radar systems such as weather radar system [2]. In other words, GaN has already been successful in wireless telecommunication and wireless sensing fields. GaN devices are seeking for the 3rd filed to be employed in.

Recently, carbon neutral (CN), or reduction of carbon dioxide (CO_2) emission has become a critical global issue and many countries and enterprises are committed for CN. There are two main issues for CN. The first one is conversion from fossil energies to reproducible natural energies. Among of reproducible natural energies, solar energy is dominant so far and will continue to be the most important part. However, solar power is susceptible to weather conditions and unstable. To address this problem, space solar power systems (SSPS) are proposed [3]. In Fig.1, an image of SSPS is shown schematically. By launching a huge satellite equipped with many solar cell panels and a microwave transmitter, solar energy is converted to microwave energy and transmitted from space to the earth. In SSPS, C-band microwave (5.8GHz) is used to transmit energy from SSPS to the earth, where microwave energy is rectified and converted to DC energy again. The efficiency of the microwave transmitter is the most important factor which determines overall efficiency of SSPS system, which is the ratio of obtained DC output power on the earth with respect to solar energy received at solar cells. GaN amplifiers is regarded suitable for the transmitting amplifier since its efficiency has become very high.

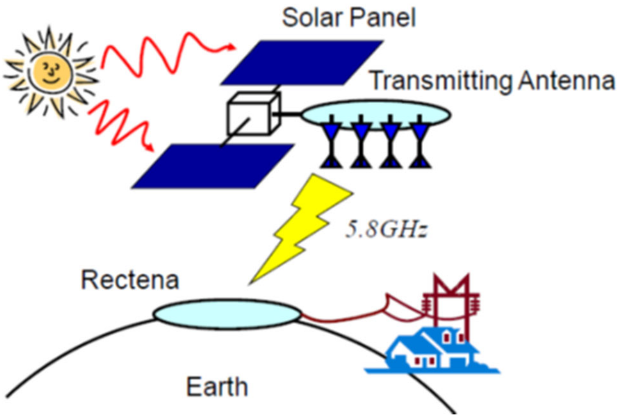

Fig.1 Space Solar Power Systems

The second point for CN is to reduce energy consumption. Roughly 1/3 of energy is consumed in the industry and heating process is dominant for the energy consumption there. So far, external heating processes such as chamber heating or steam heating have been employed. These kind of external heating methods consumes fossil energies and exhaust much CO_2. Moreover, external heating methods are very inefficient since external heating consumes energy to heat its chamber rather than heat target materials. To address this problem, microwave heating is attracting attentions [4]. Microwave can heat materials directly. Therefore, its heating efficiency is very high. In other word, microwave ovens are adopted to industrial material heat processes. For microwave heating, ISM (Industry, Science and Medical) bands have been used, such as 900MHz, 2.45GHz and 5.8GHz. Among them, 2.45GHz is the most important frequency, especially in Japan, since 900MHz is close to mobile phone band and care is needed to suppress interference. 5.8GHz is not major for ISM band so far. Components at 5.8GHz are rather costly compared with 2.45GHz.

For microwave heating, vacuum tube devices such as magnetrons have been used since microwave heating requires such high power as over 1kW. However, lifetime of magnetrons is generally short (roughly 1~3 year) and they should be replaced once every year. Recently, semiconductor-based microwave power source, namely solid-state power amplifiers (SSPAs), for microwave heating has been developed vigorously. In

Table 1, comparison of magnetron, LDMOS (Laterally Diffused Metal Oxide Semiconductor) SSPA [5] and GaN SSPA is shown. At this moment, there is no commercially available GaN SSPA for microwave heating. Therefore, GaN SSPA performance is estimated from performance of GaN high power amplifiers. From viewpoint of output power, magnetrons are superior to SSPAs. However, output power of SSPAs can be combined to get higher power, even up to some kW, since they are phase coherent. From viewpoint of efficiency, magnetron is slightly superior to SSPAs, but SSPA efficiency is getting better and better. Also, cost of SSPAs is decreasing drastically. It will be comparable to magnetron in near future. Considering material properties, GaN is more suitable than LDMOS. GaN SSPA will play important role for microwave heating to realize CN.

In this paper, 5.8GHz GaN amplifier for wireless power transfer and 2.45GHz GaN amplifier for microwave heating are reviewed. As a showcase of SSPA's merits, experimental results of microwave power concentration and uniform heating are shown. Finally, future prospect of SSPAs for microwave power transfer and microwave heating are discussed.

Table.1 Comparison of Magnetron, LDMOS and GaN

	Magnetron	LDMOS	GaN
Output Power of Single device	~6kW	~250W	~420W (expected)
Phase coherence	No	Yes	Yes
Efficiency	~70%	~60%	~65% (expected)
Cost	~$1k/kW~	~$3k/kW	TBD
Lifetime	1~3 year	~10 year	~10 year

2. 5.8GHz GaN amplifier for wireless power transfer

In Fig.2, the circuit schematic of the 5.8GHz GaN amplifier [6] is shown. It consists of a GaN HEMT chip, quarter wavelength impedance transformers and open circuited stubs for harmonic terminations. Input and output impedances of the amplifier are matched to 50 ohm. Gate length of the GaN HEMT is chosen to 0.25 micron. This short gate length GaN HEMT is usually used for Ku-band (12.4GHz~18GHz). To obtain high efficiency, harmonic tuning effect should be maximized since efficiency of the amplifier is finally determined by class of operation. To realize ideal operation class, short gate length GaN transistor is used. For input side, only the 2nd harmonic is controlled since effect of the 3rd harmonic at input side is negligible. Meanwhile, the 2nd and the 3rd harmonics are carefully controlled since both affect the efficiency of the amplifier. Positions of the harmonic reflection stubs are determined from measurement results of harmonic load-pull.

Photograph of the 5.8 GHz internally matched GaN HEMT is shown in Fig.3. Input matching circuit is made on a high dielectric substrate (ε_r=38) while output matching circuit is made on an alumina substrate. Effective circuit size is 8mm x 8mm and all circuit components are packed in a hermetically sealed metal package. The amplifier exhibited 70% power added efficiency (PAE) together with 7.1W output power with 30V drain voltage.

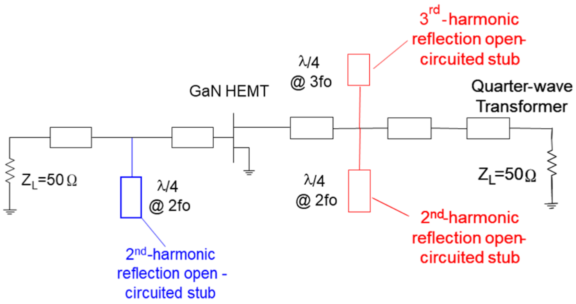

Fig.2 Circuit schematic of the 5.8GHz GaN amplifier [6]

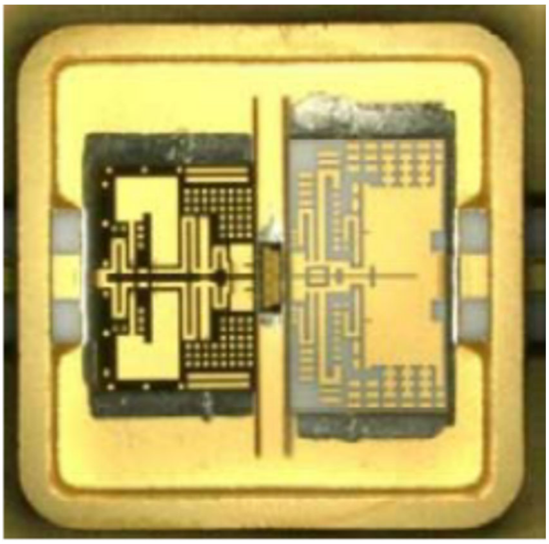

Fig.3 Photograph of the 5.8 GHz internally matched GaN HEMT high efficiency amplifier [6]

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To improve the efficiency, the easiest way is to reduce the gate length since it enhances the harmonic tuning effects. In Fig.4, output power, gain, PAE vs input power of 0.15micron GaN HEMT amplifier are shown. The circuit is almost same as shown in Fig.2 and Fig.3 except of slight tuning. 78.9% PAE was obtained together with 9W output power. This is the record high efficiency for 5.8GHz GaN amplifier for the time being. Comparison against other published works [8-14] are shown in Fig.5.

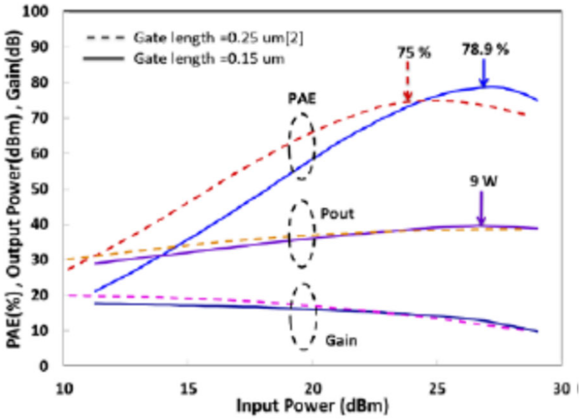


Fig.4 Output power, Gain, PAE vs input power of 0.15micron GaN HEMT amplifier [7]

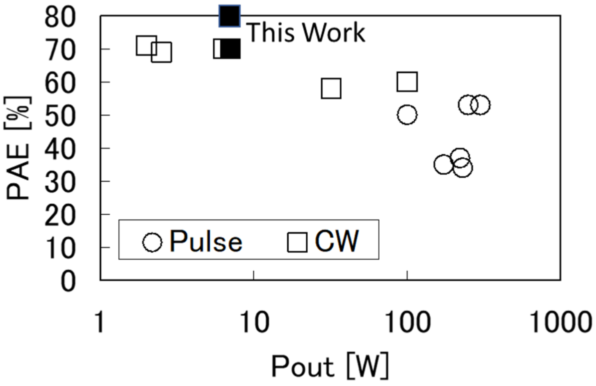


Fig.5 State-of-the-art of C-band GaN amplifiers

3. 2.45GHz GaN amplifier for microwave heating

For microwave heating, both high output power and high efficiency are required. A 400W class CW operation GaN high power amplifier is designed and manufactured [15]. In Fig.6, photo of the developed 2.45GHz high power and high efficiency GaN power amplifier is shown. It consists of two GaN HEMT chips, each has total gate width of 38.4mm. Circuit topology is same as Fig.2 except that only the 2nd harmonic is terminated (the 3rd harmonic is omitted) since the 3rd harmonic tuning was very difficult for this kind of large gate periphery chips and tuning the 3rd harmonic may cause a significant increase of circuit loss at the fundamental frequency. The 2nd harmonic at input side was terminated with on-chip pre-match circuit.

In Fig.7, measured output power, drain efficiency, gain vs input power are shown. The measurement was done with 50V drain voltage. At peak, 70% drain efficiency was successfully obtained. This number is close to that of commercially available magnetrons for microwave ovens. Considering circuit losses of SSPAs after final stage amplifiers, which is typically 0.3dB, total SSPA output power would be 420W and efficiency would be 65%.

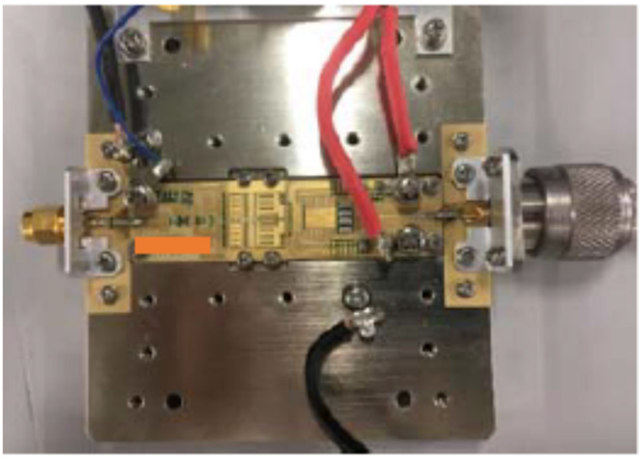


Fig.6 Photo of the developed 2.45GHz high power and high efficiency GaN power amplifier [15]

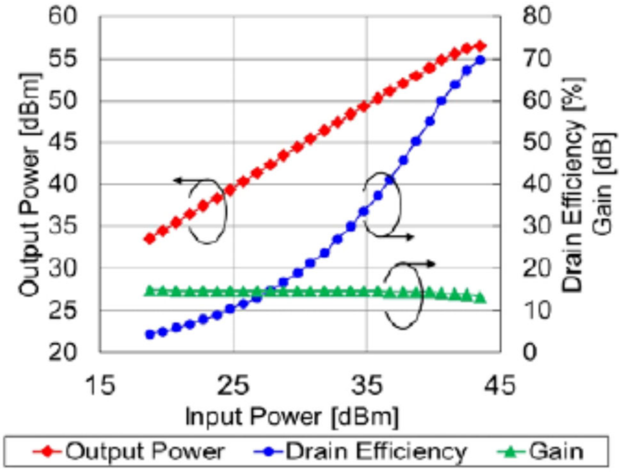


Fig.7 Output power, drain efficiency, Gain vs input power [15]

To reduce cost of GaN amplifiers, GaN-on-Si amplifier was also developed [16]. In Fig.8, measured output power, drain efficiency (DE), PAE, gain vs input power of GaN-on-Si amplifier are shown. The measurement was done with 30V drain voltage at 2.15 GHz. 170W output power was successfully obtained with peak PAE of 60%. These results are compared with other published works [17-22] in Fig. 9.

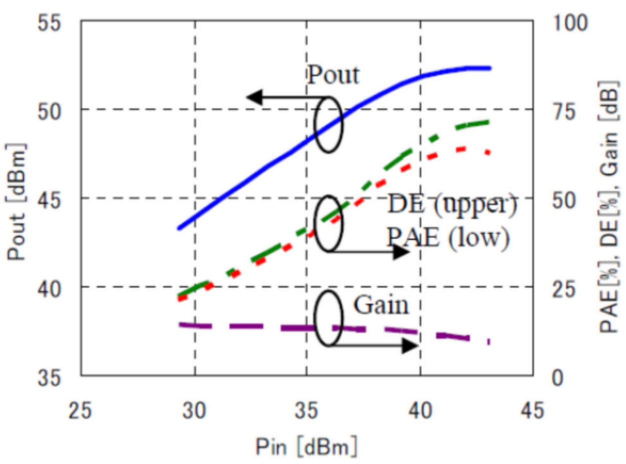


Fig.8 Output power, DE, PAE, Gain vs input power of GaN-on-Si amplifier [16]

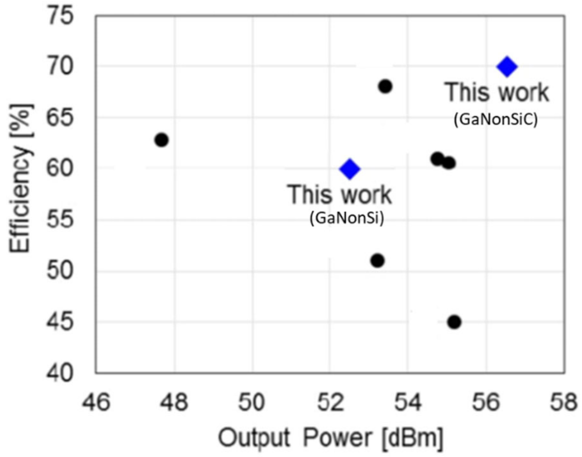


Fig.9 State-of-the-art of 2.45GHz high efficiency GaN amplifiers

4. Phase control demonstration of GaN SSPA

As is mentioned in the introduction, one of advantages of SSPA against magnetron is that SSPA is phase coherent while magnetron is NOT phase coherent, except for the case of injection locked magnetrons [23].

To demonstrate the merit of phase coherence, beam forming and steering in a microwave cavity was demonstrated [24]. Principal of phase-controlled microwave power steering is shown in Fig.10. There are 3 microwave input ports to the cavity. At each port, SSPA operating in 2.45GHz is attached together with phase shifters (A, B, C). Microwave signal from the source is divided into 3 ports, but they keep coherence. By setting phase difference between these input ports, microwave energy fed into the cavity is controlled as shown in Fig.10. To visualize microwave power, array of rectennas connected with LEDs are placed in the cavity. When a rectenna unit was irradiated by microwave, LED connected to the rectenna turns on green. Fig.11 shows the experimental result of phase-controlled microwave power concentration. By setting phase shifters A, B, C, microwave power is concentrated at the left-hand side, the center, or the right-hand side. This result means that phase-controlled microwave heating cavity can heat any part selectively.

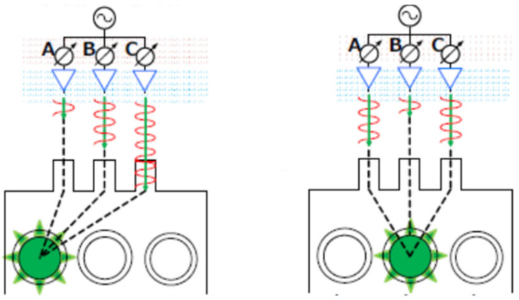


Fig.10 Principal of phase-controlled microwave power steering [24]

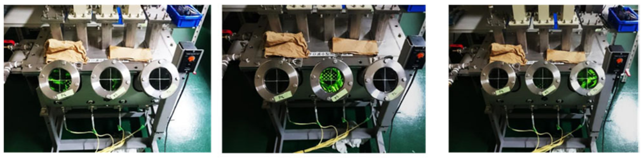
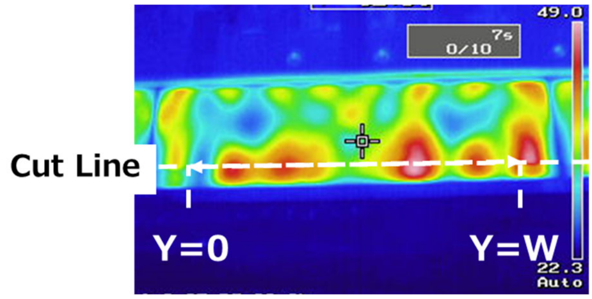

Left
Center
Right

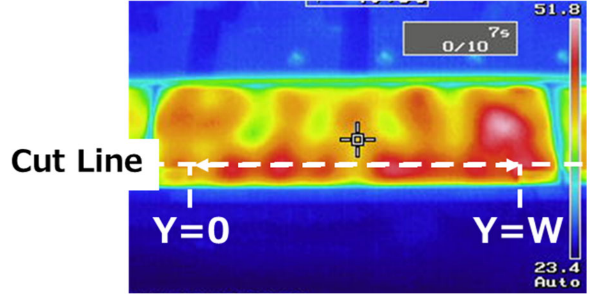
Fig.11 Experimental result of phase-controlled microwave power concentration [24]

For actual use case in the industry, uniform heating will be more important than selective heating. By setting phase difference adequately, uniform heating is also achieved [25]. In Fig.12, the results of uniform microwave heating are shown. Operating frequency is 2.45 GHz, heating area width W is 60cm, and other details of the experimental setup is described in [25]. In the figures, red part is “hot” while blue part is “cold”. As can be seen in the figures, without phase control, heat dissipation is non-uniform while it is rather uniform with phase control. Fig.13 shows the heat dissipation profiles along with the cut lines shown in Fig.12. For the case of without phase control, heat dissipation varies roughly 5 times (from 15 to 75) while fluctuation for with phase control case is as small as 16% (from 37 to 52).

As shown above, phase controlled SSPAs can realize either concentration heating or uniform heating by just setting phase differences. This capability is desirable for microwave material heating processes.



(a) Without phase control



(b) With phase control

Fig.12 . Results of uniformed microwave heating [25]

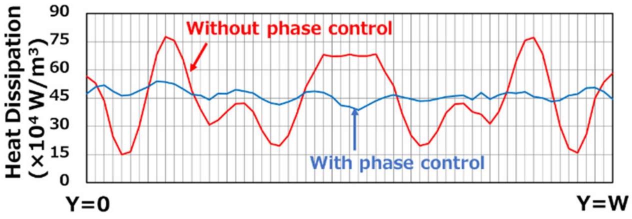


Fig.13 Heat dissipation profiles [25]

5. Future prospect of SSPAs for wireless power transfer and microwave heating

As is mentioned so far, GaN SSPAs are promising for wireless power transfer and microwave heating applications. However, there still are some challenges for SSPAs to be widely deployed in industry.

Total power should be raised to some kW at least. Some 100kW to MW will be required in future. To achieve such high power, special power combining technique is necessary. Also, power density of semiconductor devices should be higher than now. Table.2 summarizes comparison of SSPA devices in future. GaN-on-Diamond [26,27] and Diamond transistor [28,29] are considered to have several times higher power density compared with incumbent GaN-on-SiC devices. By using these devices, SSPA output power will be multiplied.

Thermal conductivity of the substrate will be crucial as power density of the device increases. GaN-on-Diamond and Diamond devices enjoy very high thermal conductivity of diamond substrate and hence are advantageous for kW operation.

One of the most important challenges for SSPA will be efficiency. Currently estimated 65% efficiency is NOT enough for GaN SSPA to be used widely. At least 70% efficiency is essential. GaN-on-GaN [30,31] is considered to have better efficiency than GaN-on-SiC. It is considered that crystalline defects which arise from hetero-epitaxy between SiC substrate and GaN epi-layer cause efficiency degradation. GaN-on-GaN, which is totally home epitaxial, will be defects free and from +5 to +10 percentage point efficiency improvement can be expected.

Another most important challenge is cost. From viewpoint of cost, GaN-on-Si device seems promising since cost of substrate is substantial for microwave power devices. However, care must be taken for the fact that GaN-on-Si device performance decreases as ambient temperature (Tamb) increases [32]. Fig.14 shows measured and simulated large-signal characteristics of GaN-on-Si transistor at room temperature (Tamb=300K) and elevated temperature (Tamb=394K). It is obvious that both output power and PAE drastically decrease as Tamb increases. By large-signal transistor model analysis, it was found that these degradations are due to increase of substrate leakage current at elevated temperature. Therefore, improvement of substrate current leakage at elevated temperature is a must for GaN-on-Si to be employed. If cost of SSPAs is decreased as low as magnetrons, SSPA will be rapidly employed in microwave heating systems.

Operation frequency is also to be considered. Currently, 900MHz, 2.45GHz and 5.8GHz are popular for wireless power transfer and microwave heating. However, higher frequency, such as 24GHz, leads to smaller size of antennas. Especially for wireless power transfer, planar array antenna is usually used for beam steering. The higher the frequency, the smaller antenna size can be. 24GHz or even higher frequency SSPAs are expected to emerge in future.

Table.2 Comparison of SSPA devices in future

	GaN-on-Dia	GaN-on-GaN	GaN-on-Si	Diamond	Ga_2O_3
Power Density	Very Good	Good	Poor	Very Good	Very Good
Thermal Conductivity	Very Good	Medium	Poor	Very Good	Poor
Cost	High	Medium	Very Low	Very High	Low?
Efficiency	Good	Very Good	Medium	Good?	Poor??
High Frequency operation	Good	Very Good	Good	Medium	Very Poor

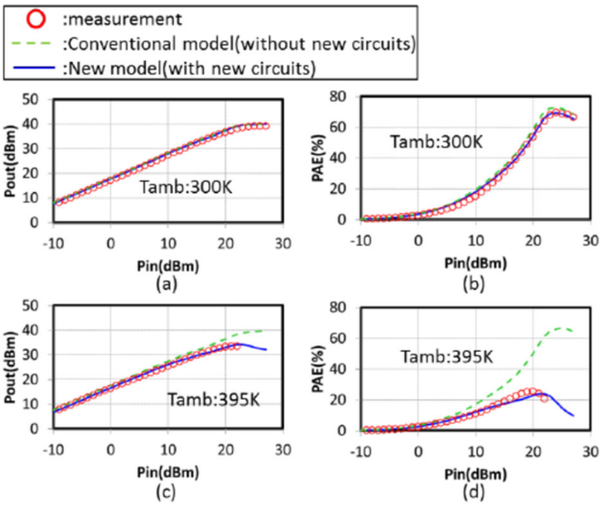


Fig.14 Measured and simulated Large-signal characteristics of the GaN-on-Si transistor at room temperature (Tamb=300K) and elevated temperature (Tamb=394K) [32]

4. Conclusion

GaN solid state power amplifiers for wireless power transfer and microwave heating have been reviewed from some published papers. By using harmonic termination, efficiencies of GaN high power amplifiers are raised to 79% for 9W for 5.8GHz amplifier and 70% 450W for 2.45GHz amplifier. These numbers are well enough for GaN SSPAs to be employed for a certain application. For wide-spread application of SSPAs, more improved performance and lower cost are desired. New devices such as GaN-on-Diamond, GaN-on-GaN, or GaN-on-Si, Diamond transistor could be candidates of future SSPAs.

Acknowledgments

The authors would like to acknowledge all the people involved in these works, which includes Prof. Toshiyuki Oishi at Saga University, Yutaro Yamaguchi, Yuji Komatsuzaki, Yoshifumi Kawamura, Keigo Nakatani, Masatake Hangai, Takaaki Yoshioka, and Jun Nishihara at Mitsubishi Electric Corporation.

The authors would like to acknowledge Kyoto University and Institute for Unmanned Space Experiment Free Flyer (USEF), an affiliate organization of Ministry of Economy, Trade, and Industry (METI), for their sponsorship to SSPS program.

Part of this work was done under sponsorship of New Energy Development Organization.

References

[1] Koji YAMANAKA, Shintaro SHINJO, Senior Members, Yuji KOMATSUZAKI, Shuichi SAKATA, Keigo NAKATANI, and Yutaro YAMAGUCHI,"Overview and Prospects of High Power Amplifier Technology Trend for 5G and beyond 5G Base Stations",IEICE TRANS. ELECTRON., VOL.E104–C, pp.526-533, NO.10 Oct. 2021.

[2] Koji YAMANAKA, Yasunori SUZUKI, Shoichi NARAHASHI, Takaya WADA, Makoto KAWASHIMA, Ken TAKEI, Kazutaka TAKAGI, Atsushi HONDA, Zhengyi LI, Liang ZHOU, Yoji OHASHI, Wataru HATTORI and Yusuke TAKAHASHI,"Recent Activities of Japanese Microwave Industry",IEICE TRANS. ELECTRON., VOL.E98–C, NO.7, pp.621-629 July 2015.

[3] N. Shinohara and S. Kawasaki, "Recent Wireless Power Transmission technologies in Japan for space solar power station/satellite", 2009 IEEE Radio and Wireless Symposium, pp.13-15, Jan. 2009.

[4] https://mwcc.jp/en/

[5] https://www.minicircuits.com/WebStore/dashboard.html?model=ZHL-2425-250X%2B

[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", Proceedings of Asia-Pacific Microwave Conference 2010, WE3A-1, Dec. 2010.

[7] M. Hangai, Y. Kimoto, K. Harauchi, Y. Yamaguchi, K. Yamanaka and Y. Homma, "0.15 um GaN amplifier for Space Solar Power Systems by gate length reduction", IEICE Society conference, Sept. 2015.

[8] Y. Kamo, T. Kunii, H. Takeuchi, Y. Yamamoto, M. Totsuka, S. Miyakuni, T. Oku, T. Nanjo, H. Chiba, T. Oishi, Y. Abe, Y. Tsuyama, R. Shirahana, H. Ohtsuka, K. Iyomasa, K. Yamanaka, M. Hieda, M. Nakayama, H. Matsuoka, Y. Tarui, T. Ishikawa,T. Takagi, K. Marumoto and Y. Matsuda, "C-Band 140 W AlGaN/GaN HEMT with Cat-CVD Technique", 2005 IEEE MTT-S Int. Microwave Symp. Dig. WE1E-4, June 2005

[9] K. Yamanaka, K. Iyomasa, H. Ohtsuka, M. Nakayama, Y.Tsuyama, T. Kunii, Y. Kamo, T. Takagi, “S and C band over 100W GaN HEMT 1chip high power amplifiers with cell division configuration,” 2005 European Gallium Arsenide and Other Semiconductor Application Symposium, pp.241-244, Oct. 2005.

[10] Y. Okamoto, A. Wakejima, Y. ando, T. Nakayama, K.Matsunaga, and H. Miyamoto, "100W C-band single-chip GaN FET power amplifier", Electronics Lett., Vol. 42, No. 5 pp.283-285, Mar. 2006.

[11] Y. Takada, H. Sakurai, K. Matsushita, K. Masuda, S. Takatsuka, M. Kuraguchi, T. Suzuki, T. Suzuki, M. Hirose, H. Kawasaki, K.Takagi, and K. Tsuda, "C-Band AlGaN/GaN HEMTs with 170W Output Power", 2005 Int. Conference on Solid State Devices and Materials, Extended Abstracts, pp.486-487, Sept. 2005.

[12] H. Shigematsu, Y. Inoue, A. Akasegawa, M. Yamada, S.Masuda, Y. Kamada, A. Yamada, M. Kanamura, T. Ohki,Makiyama, K. Okamoto, N. Imanishi, K. Kikkawa, K. Joshin,and N. Hara, “C-band 340-W and X-band 100-W GaN power amplifiers with over 50-% PAE”, 2009 IEEE MTT-S Int.Microwave Symp. Dig., pp. 1265-1268, May 2009.

[13] T. Yamasaki, Y. Kittaka, H. Minamide, K. Yamauchi, S. Miwa, S. Goto, M. Nakayama, M. Kono and N. Yoshida, "A 68% Efficiency, C-Band 100W GaN HEMT Amplifier for Space Applications", 2010 IEEE MTT-S Int. Microwave Symp. Dig. TH3D-1, May 2010.

[14] K. Kuroda, R. Ishikawa, and K. Honjo, "High-Efficiency GaN

HEMT Class-F Amplifier Operating at 5.7 GHz", Proceedings of the 38th European Microwave Conference, pp.440-443, Oct. 2008.

[15] Takumi Sugitani, Kazuhiro Iyomasa, Masatake Hangai, Yoshifumi Kawamura, Jun Nishihara, and Shintaro Shinjo, " 2.45 GHz ISM-Band 450W High Efficiency GaN Pallet Amplifier for Microwave Heating", Proceedings of Asia-Pacific Microwave Conference 2018, Dec. 2018.

[16] Takaaki YOSHIOKA, Naoki KOSAKA, Masatake HANGAI, and Koji YAMANAKA," Mitsubishi Electric's GaN High Power Amplifiers for Civil Applications", Thailand-Japan MicroWave Nov. 2014.

[17] RYP24200-20S,"220W, 2.45GHz ISM-band, GaN Pallet Amplifier", RFHIC, Available

[18] Fabian Platz, Olof Bengtsson, Adam R¨amer, Serguei A.Chevtchenko, and Wolfgang Heinrich, "2.45 GHz ISM-Band RF-PA Demonstrator for GaN-HEMT optimization," in Proc. of German Microwave Conference (GeMIC) 2014, Mar. 2014.

[19] T. Shi and K. Li,"High Power Solid-state Oscillator for Microwave Oven Applications," in 2012 IEEE MTT-S Int. Microw. Symp. Dig., June 2012.

[20] MRF24300N,"320W, 2.45GHz ISM-band, RF Power LDMOS Transistor", NXP, Available

[21] https://www.anokiwave.com/

[22] Rob McMorrow, David Corman, Andy Crofts, "All silicon mmW planar active antennas: The convergence of technology, applications, and architecture", 2017 IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS), Nov. 2017.

[21] BPC2425M9X250,"300W, 2.45GHz ISM-band, LDMOS Pallet Amplifier", AMPLEON, Available

[22] Hikaru Ikeda and Yasushi Itoh, "2.4GHz-Band High Power and High Efficiency Solid-State Injection-Locked Oscillator Using Imbalanced Coupling Resonator in Feedback Circuit," in Proc. of 2017 IEEE MTT-S Int. Microwave Symp. (IMS), June 2017

[23] Bo YANG, Tomohiko MITANI, and Naoki SHINOHARA,"Experimental Study on a 5.8 GHz Power-Variable Phase-Controlled Magnetron",IEICE TRANS. ELECTRON., VOL.E100–C, NO.10, pp.901-907, Oct. 2017.

[24] Kazuhiro IYOMASA, Koji YAMANAKA, Takeshi SHIODE, Hiroyuki MIZUTANI, Masaomi TSURU, Yoshifumi KAWAMURA, Takaaki YOSHIOKA, Yuji KOMATSUZAKI, Yutaro YAMAGUCHI, Keigo NAKATANI, Ryuta KOMARU, and Hiroshi FUKUMOTO, "Industrial microwave heating device using GaN amplifier module", IEICE Technical Report, Nov. 2016.

[25] Kazuhiro IYOMASA, Yoshifumi KAWAMURA, Ryota KOMARU, Yutaro YAMAGUCHI, Keigo NAKATANI, Takeshi SHIODE,Koji YAMANAKA, Kazutomi MORI and Hiroshi FUKUMOTO,"Demonstration of Uniform Heating Distribution Control for Microwave Heating Small Reactor with Solid-State Oscillators", IEICE Technical Report, Oct. 2017.

[26] Won Sang Lee, Kyung Won Lee, Seung Hyun Lee, Kevin Cho and Samuel Cho,"A GaN/Diamond HEMTs with 23 W/mm for Next Generation High Power RF Application",2019 IEEE/MTT-S International Microwave Symposium, pp.1395-1398, June 2019.

[27] https://www.mitsubishielectric.com/news/2019/0902.html.

[28] Makoto KASU, Kenji UEDA, Hiroyuki KAGESHIMA, and Yoshiharu YAMAUCHI,"RF Equivalent-Circuit Analysis of p-Type Diamond Field-Effect Transistors with Hydrogen Surface Termination", IEICE TRANS. ELECTRON., VOL.E91–C, NO.7, pp.1042-1049, July 2008.

[29] Hitoshi UMEZAWA, Shingo MIYAMOTO, Hiroki MATSUDAIRA, Hiroaki ISHIZAKA, Kwang-Soup SONG, Minoru TACHIKI and Hiroshi KAWARADA,"RF Performance of Diamond Surface-Channel Field-Effect Transistors", IEICE TRANS. ELECTRON., VOL.E86–C, NO.10, pp.1949-1954, Oct. 2003.

[30] Masaru SATO, Yusuke KUMAZAKI, Naoya OKAMOTO, Toshihiro OHKI, Naoko KURAHASHI, Masato NISHIMORI, Atsushi YAMADA, Junji KOTANI, Naoki HARA and Keiji WATANABE,"Uniform/Selective Heating Microwave Oven Using High Efficiency GaN-on-GaN HEMT Power Amplifier",IEICE TRANS. ELECTRON., VOL.E106–C, NO.10, pp.605-613, Oct. 2023.

[31] https://xtech.nikkei.com/atcl/nxt/column/18/02277/120500008/?P=3

[32] Yutaro Yamaguchi, Shintaro Shinjo, Koji Yamanaka and Toshiyuki Oishi,"Large signal mdoel of GaN-on-Si by taking into account temperature dependence of RF leakage at substrate", IEICE Society conference, Sept. 2016.