INVITED PAPER *Special Section on Microwave and Millimeter-Wave Technologies*

Overview and Prospects of High Power Amplifier Technology Trend for 5G and beyond 5G Base Stations

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SUMMARY High power amplifier technologies for base transceiver stations (BTSs) for the 5th generation (5G) mobile communication systems and so-called beyond 5G (B5G) systems are reviewed. For sub-6, which is categorized into frequency range 1 (FR1) in 5G, wideband Doherty amplifiers are introduced, and a multi-band load modulation amplifier, an envelope tracking amplifier, and a digital power amplifier for B5G are explained. For millimeter wave 5G, which is categorized into frequency range 2 (FR2), GaAs and GaN MMICs operating at around 28GHz are introduced. Finally, future prospect for THz GaN devices is described.
key words: *5G, beyond 5G, high power amplifier, base-station, Doherty amplifier, digital power amplifier*

1. Introduction

In 2019, the 5th generation mobile communication (5G) service has started in Korea, United States, and other countries. In Japan, 5G started in March 2020. In 5G systems, the maximum data transmission rate is upgraded up to 20 Gbps, which is roughly 20 times higher than that of the 4th generation mobile telecommunication (4G) systems. The maximum number of devices connected in a certain area is also extended to 1,000,000 devices/km^2, which is 10 times larger than that of 4G, and access delay (latency) is shortened to 1ms, which is 1/10 of that of 4G. In addition, the next generation system, which is called beyond 5G (B5G) or 6G, has started to be discussed in the world [1], [2]. In B5G, a further higher maximum data rate, a further larger number of connected devices, and further lower latency are expected.

To realize the above-mentioned performance, high power amplifiers (HPAs) deployed in BTSs need to have superior performance to those employed in 4G BTSs. In Table 1, the 4G, 5G, and B5G HPA technology trend is summarized.

In 5G, millimeter wave (mmW) frequencies are used together with lower microwave frequencies, which are so called “sub-6” [3]. In B5G, THz (140 GHz band and 300 GHz band) will be added to the 5G frequency allocation list for higher bit rates. The maximum instantaneous bandwidth of 5G is 4 times larger than that of 4G. This means HPAs have to operate with a broader bandwidth. It will replace existing LDMOS (Laterally Diffused Metal Oxide Semiconductor) with GaN since GaN is inherently advantageous to broadband operation. The instantaneous bandwidth required in B5G will be further broad, 10 GHz, for example. But that is not certain because the discussion about the B5G systems has just started. In 4G, so-called macro BTS played a critical role, while in 5G, massive MIMO BTS that employs at least 16 to 64 HPAs in an antenna will play a more important role. That is why typical average output power (Pave) becomes smaller. In B5G, Pave required will be further smaller since area coverage for each BTS will be smaller for higher space division multiplexing.

Table 1 Summary of the 4G/5G/B5G HPA characteristics trend

	4G	5G	B5G (6G)
Maximum data rate	1Gbps	20Gbps	100Gbps
Maximum # of devices	0.1M/km^2	1M/km^2	10M/km^2
Latency	10ms	1ms	0.1ms
Allocated Frequencies in Japan (including future expectation)	800MHz~ 3400MHz	600MHz~ 4900MHz + 27.5GHz~ 31.5GHz	5G frequencies + THz(140GHz, 300GHz)
Maximum instanteneous bandwidth	20MHz	100MHz(sub6) 800MHz(mmW)	up to 10GHz?
Typical average output power (Pave) for sub6 HPA	40W	5W	1W
Typical back-off of Pave from saturaed power (Psat)	7dB	8.5dB	>10dB
Device Technologies	LDMOS	LDMOS/GaN (sub6) CMOS/GaAs /GaN(mmW)	GaN(sub6) CMOS/GaAs /GaN (mmW+THz)

Typical back-off of 5G is a little bit higher than that of 4G, but there is no big difference. Meanwhile, in B5G, it will become larger, e.g. 10 dB, since in B5G systems, BTS output power should be changed depending on data traffic more adaptively than that in 5G systems in order to save power consumption in the BTS.

In this review paper, some HPA technologies for 5G and B5G are introduced. In chapter 2, an HPA technology trend in sub-6 is explained. In chapter 3, a mmW and THz HPA technology trend is explained, followed by the summary.

Manuscript received January 20, 2021.
Manuscript revised March 1, 2021.
Manuscript publicized May 13, 2021.
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DOI: 10.1587/transele.2021MMI0008

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2. HPA Technology Trend in sub6 GHz

In Fig. 1, the BTS HPA technology trend is shown schematically [4]. Doherty amplifier technology has been used since 3G, and most of BTS HPAs in sub-6 are still based on the Doherty amplifier technology. Although the conventional analogue Doherty amplifiers are advantageous to enhance back-off efficiency for around 6 dB back-off, it is not suitable for wide-band operation since the conventional analogue Doherty amplifiers usually employ quarter wave-length transmission lines. An optimum back-off power level for efficiency enhancement can be tuned by changing the output power ratio of a carrier (or main) amplifier to a peak (or auxiliary) amplifier. However, as the optimum back-off level goes up over 6 dB, the modulation-signal-based efficiency in the analogue Doherty amplifiers suffers from a relative large dip of efficiency observed in between the optimum back-off power level and the saturation power level. Moreover, an operation bandwidth for the Doherty amplifiers becomes narrower as the output power ratio becomes larger. To address these problems, some new types of Doherty amplifiers have been proposed to date [5]–[13]. For efficiency enhancement at arbitrary back-off levels, GaN envelope tracking (ET) amplifiers have already been proposed [14], [15]. It has long been considered that ET amplifier is NOT suitable for BTS HPAs. Although high-voltage and large-current operation is required for the BTS HPAs, it was not easy for envelope amplifiers to handle such high voltage and high current. However, by using GaN for both an RF amplifier and an envelope amplifier, an ET BTS HPA has become realistic. As the need for the arbitrary back-off operation becomes more important, it is considered that a digital controlled transmitter with a switching amplifier will be employed finally.

In Fig. 2, the photo of a wideband GaN Doherty power amplifier with a frequency dependency compensating circuit (FDCC) is shown [5]. As mentioned before, the conventional Doherty amplifiers are not good at wideband operation, because a quarter wave-length transmission line connected to the output of main amplifier limits the operational bandwidth. The Doherty amplifier shown in Fig. 2 features a novel FDCC that consists of a half wave-length transmission line attached to the output of the peak amplifier. This FDCC compensates for the parasitic reactance generated by the quarter wave-length transmission. Measured frequency dependences of drain efficiency (DE) and output power with ACLR using a digital predistortion (DPD) are shown in Fig. 3 [5], where DE and output power at ACLR < -50 dBc are plotted. Thanks to the FDCC, more than 34.3 dBm of output power and more than 45% of DE are successfully obtained over a 400 MHz operational bandwidth. This is well enough to cover 4 channels of a 5G new radio (NR) 100 MHz signal bandwidth.

To employ the Doherty amplifier configuration shown in Fig. 2 in realistic massive-MIMO 5G antennas, the circuit area occupied by the amplifier should be miniaturized to far less than unit antenna separation, typically 30 mm. The photo of the fully-integrated 2 stage GaN Doherty power amplifier module with a compact FDCC is shown in Fig. 4 [16]. Matching circuits consist of lumped element chip capacitors, chip inductors, and transmission lines fabricated on a laminate. The module size is as small as 10 mm x 6 mm. Performance of the module with a compact FDCC

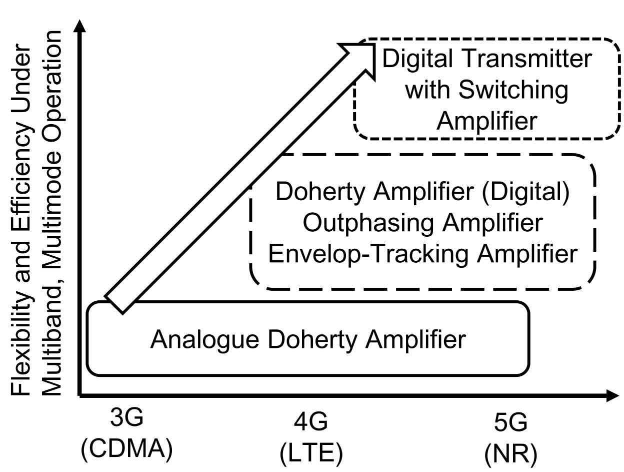

Fig. 1 BTS HPA technology trend in sub6 GHz [4]

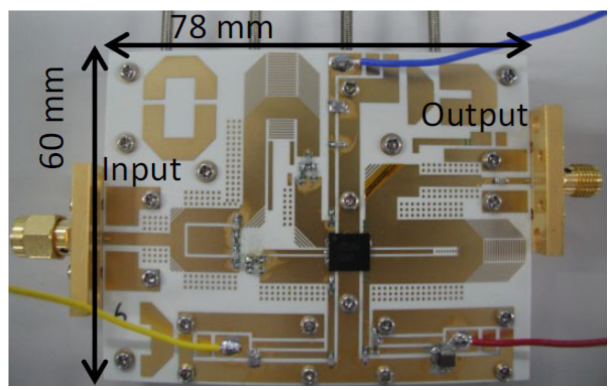

Fig. 2 Photo of wideband GaN Doherty power amplifier with frequency dependency compensating circuit (FDCC) [5]

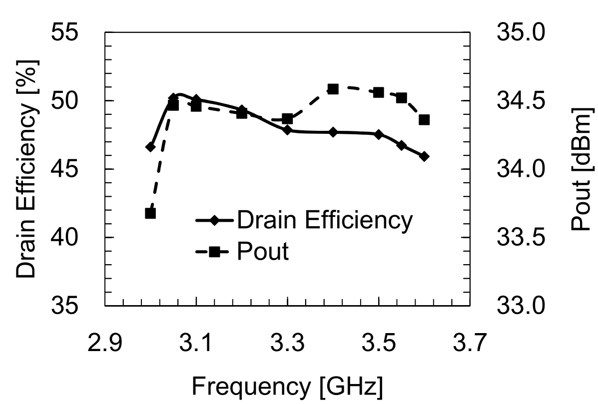

Fig. 3 Measured frequency dependences of DE and output power with ACLR of −50 dBc with DPD [5]

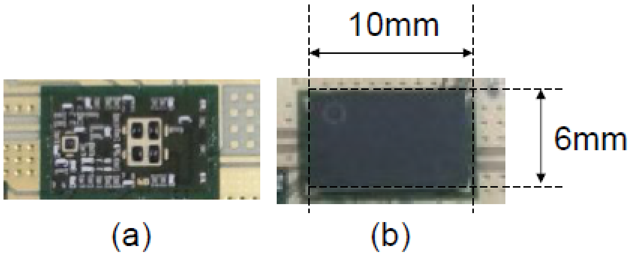

Fig. 4 Photo of the fully-integrated 2-stage GaN Doherty power amplifier module with a compact FDCC (a) before molding and (b) after molding [16]

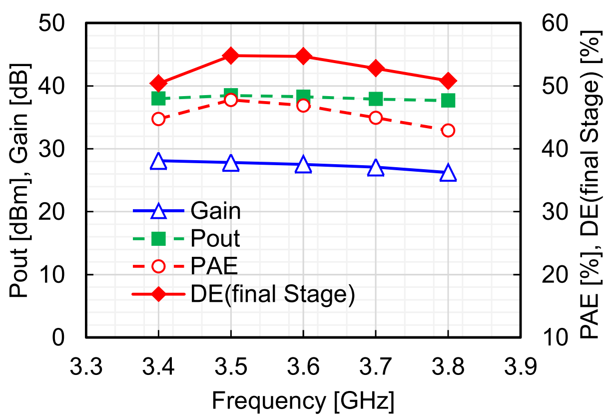

Fig. 5 Performance of the 2-stage GaN DPA Module with a compact FDCC after molding [16]

after molding is shown in Fig. 5 [16]. More than 37.5 dBm output power and 43% power added efficiency (PAE) are obtained over 3.4 to 3.8 GHz, which is globally used for 5G sub-6 applications.

The Doherty power amplifier module shown in Fig. 4 is well enough for the early stage of 5G. However, in the later stage of 5G or in the B5G era, it is considered that multiple spectrums in both 4G and 5G will be used to enhance the spectral efficiency. To fulfil the condition, BTS amplifiers should be able to operate in every frequency band of 4G and 5G. In the case of Japan, 800 MHz to 4.9 GHz operation (including so-called local 5G) is required for the BTS amplifiers. To realize such broadband operation fully a new-type load modulation amplifier is proposed.

In Fig. 6, photo of a frequency-periodic load modulated GaN power amplifier is shown [17]. In Fig. 7, measured frequency dependences of drain efficiency and output power at 6 dB power back-off level are shown [17]. The amplifier is not a conventional load modulated amplifier, but a dual input load modulated amplifier. By controlling the power ratio of the two inputs (RFin1 and RFin2) and phase difference between RFin1 and RFin2, periodic occurrence of Doherty amplifier operation and outphasing amplifier operation is realized. By doing so, more than 30 dBm output power and more than 45% drain efficiency is obtained over 1.4 GHz to 4.8 GHz. This is not enough to fully cover 800 MHz to 4900 MHz range. But, most of the 4G and 5G frequency

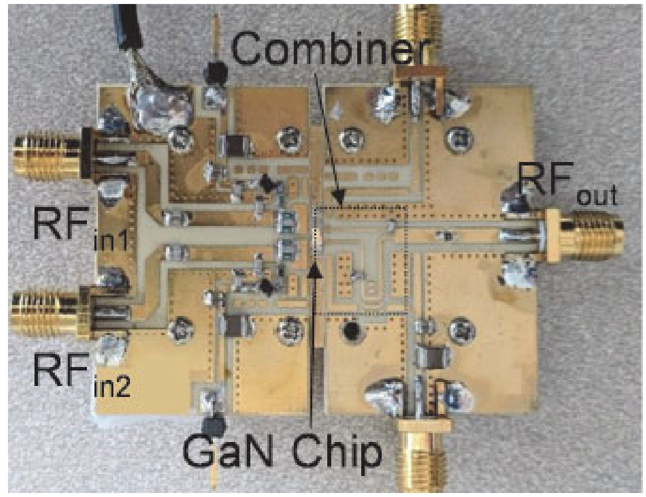

Fig. 6 Photo of a frequency-periodic load modulated GaN power amplifier [17]

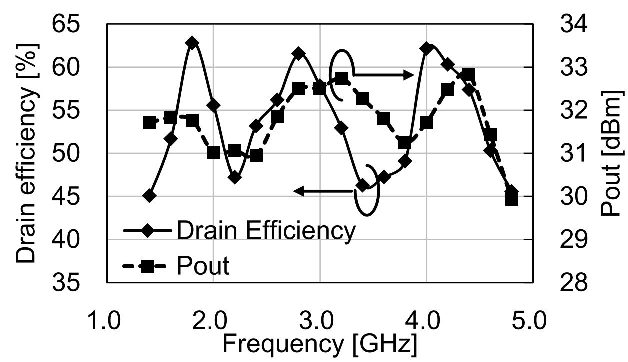

Fig. 7 Measured frequency dependences of drain efficiency and output power at 6 dB power back-off level [17]

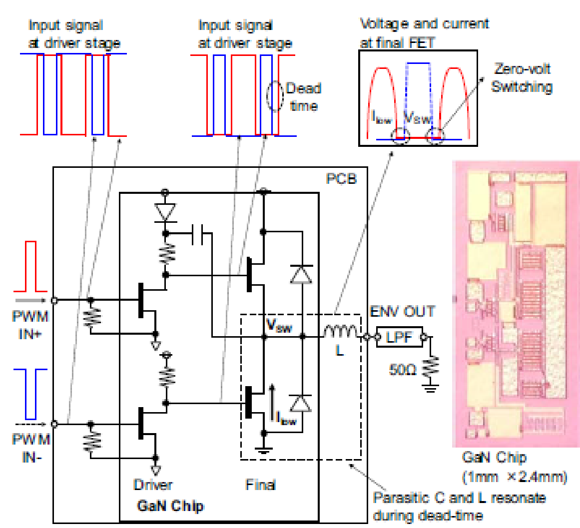

Fig. 8 Circuit diagram of the soft-switching buck-converter and chip photo [14]

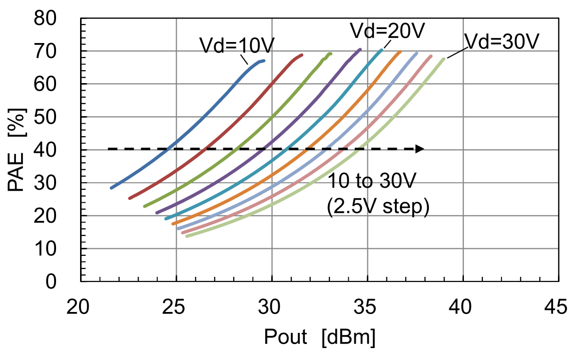

Fig. 9 Measured PAE vs. output power of RF amplifier for ET at 3.6 GHz with various fixed power supply voltages [14] Conversion efficiency of buck-converter is not included.

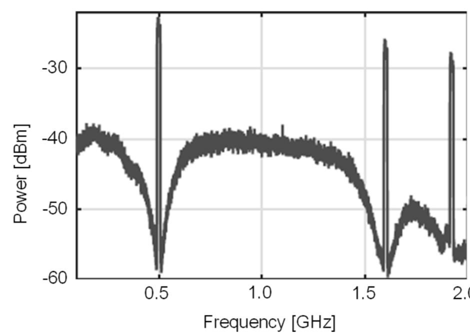

Fig. 11 A spectrum with a full span of 2.5 GHz for the carrier frequencies of 500 MHz, 1.6016 GHz, and 1.9219 GHz with a bandwidth of 18.75 MHz [21]

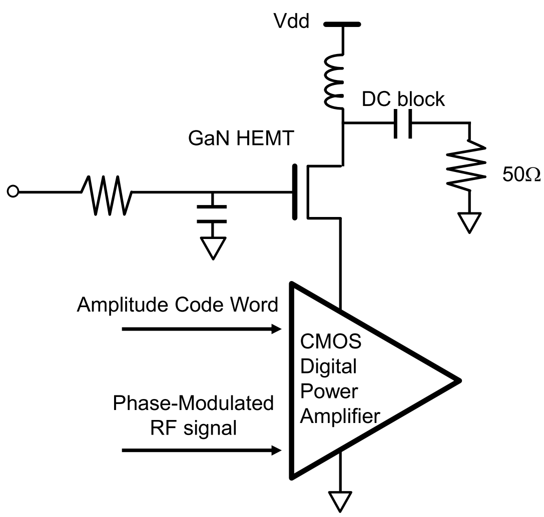

Fig. 10 Schematic of a CMOS/GaN digital power amplifier [18]

bands are covered.

The circuit diagram of the soft-switching buck-converter and GaN chip photo employed in the GaN ET amplifier are shown in Fig. 8 [14]. By using a GaN-based buck-converter configuration, high power and high conversion efficiency are realized simultaneously [15]. Moreover, with the resonance of parasitic capacitance and inductance, the current waveform is switched on and off softly, thereby resulting in the great reduction in switching noise without sacrificing efficiency. In Fig. 9, measured PAE vs. output power of RF amplifier for ET amplifier at 3.6 GHz is shown as a parameter of power supply voltage [14]. Conversion efficiency of buck-converter is not included. What is worth noticeable is that maximum drain efficiency is almost constant for power supplies ranging from 10 V to 30 V. Over almost 10 dB output power dynamic range, the drain efficiency is quite high and flat. It means that even in more than 10 dB back-off condition that is probably required for B5G BTSs, this amplifier can operate with high efficiency.

It is considered that the ultimate circuit configuration for BTS HPA is a digital switching amplifier since it is highly efficient and highly flexible at the same time [18]–[20]. One of such digital switching amplifiers is shown in Fig. 10 [18]. It uses a GaN FET connected with a silicon CMOS digital power amplifier. The CMOS digital power amplifier is capable of producing any kind of modulation signal at any frequency within transistor's transition frequency (Ft), but output power is small. Meanwhile, a GaN FET is capable of handling high power. By driving the GaN FET with the CMOS digital power amplifier, digital HPA operation is realized.

One of the benefits of employing DPA is generation of multi-tone signals. One example of an FPGA (Field Programmable Gate Array)-based all-digital RF transmitter is shown in Fig. 11 [21]. Three carrier signals at 500 MHz, 1.6 GHz and 1.92 GHz are generated.

3. HPA Technology Trend in Millimeter-Wave

As is mentioned in Introduction, mmW (e.g. 27.5 GHz ~ 31 GHz) is also used in 5G. 5G mmW BTS is classified into the following three categories; (a) short range BTS that is used for in-room or spot area high speed wireless connections, where EIRP (Equivalent Isotropic Radiation Power) is, e.g. 45 dBm. (b) Middle range BTS for last one mile connection or FWA (Fixed Wireless Access), where EIRP is, e.g. 60 dBm. (c) Long range BTS which is used for wireless back-haul connections, where EIRP is, e.g. 70 dBm. To the short range BTS, an integrated silicon RF-IC [22], [23] solution will be advantageous since it is generally low cost. For the middle range BTS, a GaAs MMIC solution can be used since output power of GaAs MMICs is 10 dB to 15 dB higher than that of silicon RF-ICs [24]–[26]. One example of GaAs MMIC frontend modules (FEMs) operating in a 28 GHz band is shown in Fig. 12 [24]. A massive MIMO antenna, which consists of 64 RF FEMs shown in Fig. 12 exhibits a maximum data transmission rate of 25.5 Gbps.

For the long range BTSs, a GaN solution will be more likely to be used because its output power is far higher than that of silicon RF-IC or GaAs MMIC. One example of GaN MMIC high power amplifiers operating around 28 GHz is shown in Fig. 12 [27]. The final stage of the amplifier is Doherty configuration to enhance efficiency at a back-off condition. Doherty operation is hard to realize at the usual

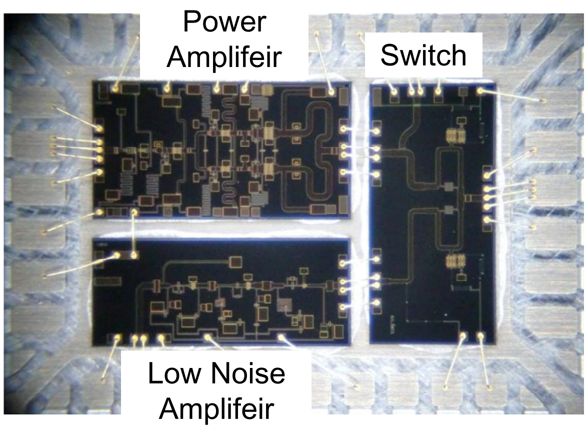

Fig. 12 Photo of fabricated GaAs RF frontend module [24]

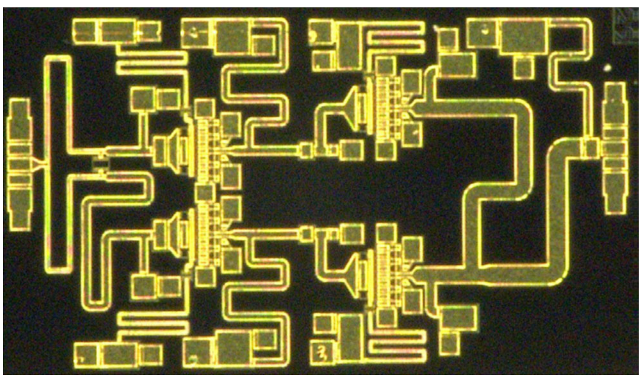

Fig. 13 Photograph of the GaN Doherty Amplifier MMIC [27]

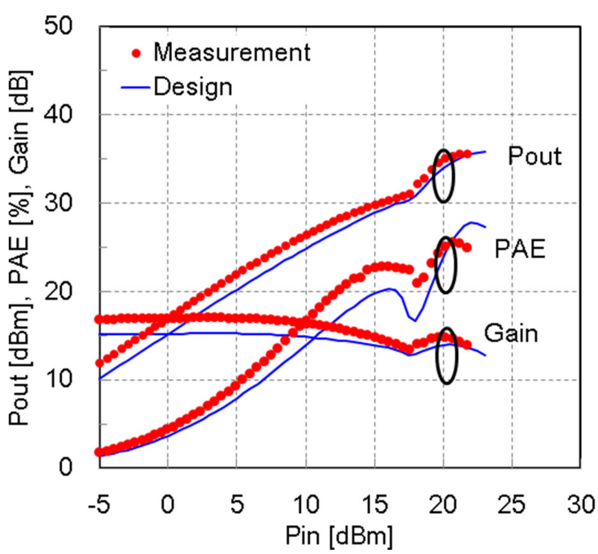

Fig. 14 Measured and simulated large-signal characteristics of the MMIC amplifier under CW operation at Vd = 24 V, IdqMain = 50 mA/mm and IdqAux = 0 mA/mm. Frequency is 28.5 GHz [27]

mmW frequencies because parasitic capacitance of transistor prevents load modulation behavior that is essential to Doherty operation. In the amplifier shown in Fig. 13, parasitic capacitance is cancelled with short-circuited stubs so

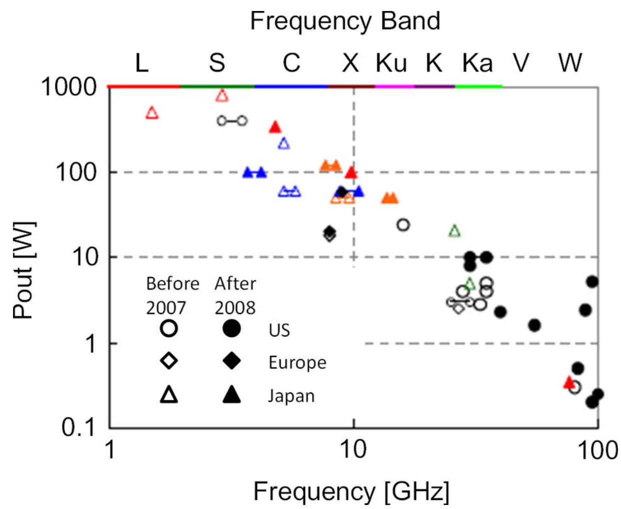

Fig. 15 State-of-the-art output power of GaN devices [31]

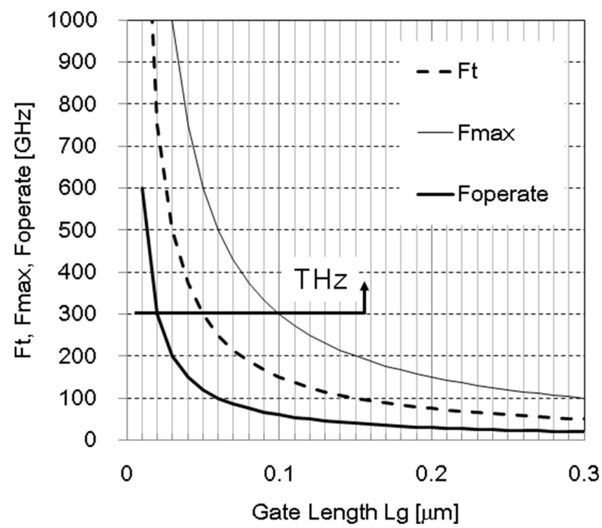

Fig. 16 Estimated Ft, Fmax and Foperate for short gate GaN FET [31]

that load modulation effect is induced. Measured Pin-Pout, PAE and Gain curves are shown in Fig. 14 together with simulated (or designed) curves [27]. Each curve exhibits an inflection point at around Pin = 18 dBm, which shows a load modulation in Doherty amplifier configuration. PAE at saturation is 25% and PAE at 6 dB back-off (Pin = 15 dBm) is 23%. In typical class-A amplifiers, efficiency at 6 dB back-off is one-fourth of saturation efficiency. That means the Doherty configuration successfully enhances PAE at 6 dB back-off by 17 percentage points.

Carrier frequency of BTS will be raised up to THz in the B5G era. There have already been some reports on the THz (over 100 GHz) operation RF-ICs [28], [29]. Some promising results for possible THz GaN devices have also been reported [30]. Figure 15 summarizes the state-of-the-art output power of GaN devices [31]. Output power tends to decrease in inverse proportion to operation frequency. However, more than 5 W of output power has been reported at around 100 GHz.

Generally speaking, maximum oscillation frequency (Fmax) and Ft of field effect transistors are inversely proportional to gate length (Lg). It is also empirically known that a practical maximum operating frequency (Foperate) is proportional to Fmax and Ft. In Fig. 16, Ft, Fmax, and Foperate, which are estimated from experimental results in literatures, is shown [31]. The figure suggests that Fmax of GaN FET will exceed 300 GHz when Lg becomes smaller than 0.1μm.

As Lg goes down below 0.02 μm, or 20 nm, Foperate will reach 300 GHz. Considering that a 20 nm lithography process is no more special process in silicon CMOS technology, THz GaN devices deployed in B5G BTS will be likely to appear within a decade.

4. Conclusion

HPA technology for BTS trends have been overviewed on the basis of several published papers. In sub-6, namely below 6GHz 5G, small form-factor and wide-band GaN HPA modules is used in 5G, whereas broadband HPAs that will cover 4G and 5G frequencies and envelope tracking HPA will be used in B5G. Finally, BTS HPAs will move to digital power amplifiers. In mmW operation, silicon RFICs, GaAs MMICs and GaN MMICs are used for high data rate 5G BTS. Operating frequency will exceed 100 GHz in B5G, where Si RF-ICs and GaN MMICs will be used.

Acknowledgments

The authors would like to acknowledge all the people involved in these works, especially Prof. Peter Asbeck in University California San Diego, Dr. Rui Ma, Dr. Koon Teo, and Dr. Phil Orlik in Mitsubishi Electric Research Laboratory, Prof. Ilthco Angelov in Chalmers University of Technology, Prof. Toshiyuki Oishi in Saga University, and Dr. Sandro Lanfranco in Nokia Bell laboratory for their continuous collaborations.

References

[1] https://www.oulu.fi/6gflagship/
[2] https://www.nttdocomo.co.jp/english/corporate/technology/whitepaper_6g/
[3] https://www.tele.soumu.go.jp/e/index.htm
[4] R. Ma, K.H. Teo, S. Shinjo, K. Yamanaka, and P.M. Asbeck, "A GaN PA for 4G LTE-Advanced and 5G: Meeting the Telecommunication Needs of Various Vertical Sectors Including Automobiles, Robotics, Health Care, Factory Automation, Agriculture, Education, and More," IEEE Microw. Mag., vol.18, no.7, pp.77–85, Nov.-Dec. 2017.
[5] Y. Komatsuzaki, K. Nakatani, S. Shinjo, S. Miwa, R. Ma, and K. Yamanaka, "3.0–3.6 GHz wideband, over 46% average efficiency GaN Doherty power amplifier with frequency dependency compensating circuits," 2017 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR), p.22, 2017.
[6] J. Shao, R. Ma, K.H. Teo, S. Shinjo, and K. Yamanaka, "A fully analog two-way sequential GaN power amplifier with 40% fractional bandwidth," 2015 IEEE International Wireless Symposium (IWS 2015), 2015.
[7] C.M. Andersson, E. Kuwata, Y. Kawamura, S. Shinjo, and K. Yamanaka, "A 0.85 – 2.7 GHz two-cell distributed GaN power amplifier designed for high efficiency at 1-dB compression," 2015 European Microwave Conference (EuMC), 2015.
[8] J. Shao, R. Ma, S. Shinjo, S. Chung, and K.H. Teo, "Design of broadband three-way sequential power amplifiers," 2016 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT), 2016.
[9] S. Niu, A.M. Koushik, R. Ma, K.H. Teo, S. Shinjo, and Y. Komatsuzaki, "Stochastically approximated multiobjective optimization of dual input digital Doherty Power Amplifier," 2017 IEEE 10th International Workshop on Computational Intelligence and Applications (IWCIA), 2017.
[10] R. Ma, M. Benosman, K.A. Manjunatha, Y. Komatsuzaki, S. Shinjo, K.H. Teo, and P.V. Orlik, "Machine-Learning Based Digital Doherty Power Amplifier," 2018 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT), 2018.
[11] S. Honda, S. Sakata, Y. Komatsuzaki, and S. Shinjo, "Efficiency Enhancement of GaN Doherty Power Amplifier at Large Power Back-Off with Virtual Short Stub Technique," 2019 IEEE Asia-Pacific Microwave Conference (APMC), 2019.
[12] S. Sakata, Y. Komatsuzaki, and S. Shinjo, "Adaptive Input-Power Distribution in Doherty Power Amplifier using Modified Wilkinson Power Divider," 2020 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR), 2020.
[13] Y. Komatsuzaki, R. Ma, S. Sakata, K. Nakatani, and S. Shinjo, "A Dual-Mode Bias Circuit Enabled GaN Doherty Amplifier Operating in 0.85-2.05GHz and 2.4-4.2GHz," 2020 IEEE/MTT-S International Microwave Symposium (IMS), 2020.
[14] Y. Komatsuzaki, S. Lanfranco, T. Kolmonen, O. Piirainen, J.K. Tanskanen, S. Sakata, R. Ma, S. Shinjo, K. Yamanaka, and P. Asbeck, "A High Efficiency 3.6-4.0 GHz Envelope-Tracking Power Amplifier Using GaN Soft-Switching Buck-Converter," 2018 IEEE/MTT-S International Microwave Symposium – IMS, p.465, 2018.
[15] S. Sakata, S. Lanfranco, T. Kolmonen, O. Piirainen, T. Fujiwara, S. Shinjo, and P. Asbeck, "An 80MHz modulation bandwidth high efficiency multi-band envelope-tracking power amplifier using GaN single-phase buck-converter," 2017 IEEE MTT-S International Microwave Symposium (IMS), 2017.
[16] S. Sakata, K. Kato, E. Teranishi, T. Sugitani, R. Ma, K. Chuang, Y.-C. Wu, K. Fukunaga, Y. Komatsuzaki, K. Horiguchi, K. Yamanaka, and S. Shinjo, "A Fully-Integrated GaN Doherty Power Amplifier Module with a Compact Frequency-Dependent Compensation Circuit for 5G massive MIMO Base Stations," 2020 IEEE/MTT-S International Microwave Symposium (IMS), p.712, 2020.
[17] Y. Komatsuzaki, R. Ma, M. Benosman, Y. Nagai, S. Sakata, K. Nakatani, and S. Shinjo, "A Novel 1.4-4.8 GHz Ultra-Wideband, over 45% High Efficiency Digitally Assisted Frequency-Periodic Load Modulated Amplifier," 2019 IEEE MTT-S International Microwave Symposium (IMS), p.706, 2019.
[18] V. Diddi, S. Sakata, S. Shinjo, V. Vorapipat, R. Eden, and P. Asbeck, "Broadband digitally-controlled power amplifier based on CMOS / GaN combination," 2016 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), p.258, 2016.
[19] S. Chung, R. Ma, S. Shinjo, H. Nakamizo, K. Parsons, and K.H. Teo, "Concurrent Multiband Digital Outphasing Transmitter Architecture Using Multidimensional Power Coding," IEEE Trans. Microw. Theory Techn., vol.63, no.2, pp.598–613, 2015.
[20] S. Chung, R. Ma, S. Shinjo, K. Yamanaka, and K.H. Teo, "A concurrent triple-band digital transmitter using feedforward noise cancellation for delta-sigma modulation," 2017 12th European Microwave Integrated Circuits Conference (EuMIC), 2017.

[21] D.C. Dinis, R. Ma, S. Shinjo, K. Yamanaka, K.H. Teo, P.V. Orlik, A.S.R. Oliveira, and J. Vieira, "A Real-Time Architecture for Agile and FPGA-Based Concurrent Triple-Band All-Digital RF Transmission," IEEE Trans. Microw. Theory Techn., vol.66, no.11, pp.4955–4966, 2018.
[22] https://www.anokiwave.com/
[23] R. McMorrow, D. Corman, and A. 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), 2017.
[24] S. Shinjo, K. Nakatani, J. Kamioka, R. Komaru, H. Noto, H. Nakamizo, S. Yamaguchi, S. Uchida, A. Okazaki, and K. Yamanaka, "A 28GHz-band highly integrated GaAs RF frontend Module for Massive MIMO in 5G," 2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G), 2018.
[25] K. Nakatani, Y. Komatsuzaki, S. Shinjo, J. Kamioka, R. Komaru, H. Nakamizo, K. Miyawaki, and K. Yamanaka, "A highly integrated RF frontend module including Doherty PA, LNA and switch for high SHF wide-band massive MIMO in 5G," 2017 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR), 2017.
[26] S. Shinjo, K. Nakatani, K. Tsutsumi, and H. Nakamizo, "Integrating the Front End: A Highly Integrated RF Front End for High-SHF Wide-Band Massive MIMO in 5G," IEEE Microw. Mag., vol.18, no.5, pp.31–40, July-Aug. 2017.
[27] K. Nakatani, Y. Yamaguchi, Y. Komatsuzaki, S. Sakata, S. Shinjo, and K. Yamanaka, "A Ka-Band High Efficiency Doherty Power Amplifier MMIC using GaN-HEMT for 5G Application," 2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G), 2018.
[28] K. Takano, S. Amakawa, K. Katayama, S. Hara, R. Dong, A. Kasamatsu, I. Hosako, K. Mizuno, K. Takahashi, T. Yoshida, and M. Fujishima, "17.9 A 105Gb/s 300GHz CMOS transmitter," 2017 IEEE International Solid-State Circuits Conference (ISSCC), 2017.
[29] S. Lee, S. Hara, T. Yoshida, S. Amakawa, R. Dong, A. Kasamatsu, J. Sato, and M. Fujishima, "An 80-Gb/s 300-GHz-Band Single-Chip CMOS Transceiver," IEEE J. Solid-State Circuits, vol.54, issue 12, pp.3577–3588, Dec. 2019. DOI: 10.1109/JSSC.2019.2944855
[30] I. Watanabe, Y. Yamashita, and A. Kasamatsu, "Research and Development of GaN-based HEMTs for Millimeter- and Terahertz-Wave Wireless Communications," 2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT), 2020.
[31] K. Yamanaka, T. Oishi, K. Yamauchi, H. Uchida, and E. Kuwata, "Current Status and Future Prospect of High Frequency GaN Devices," MWP-THz Joint Workshop, NICT, Koganei, 4th Feb. 2011.

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