INSIGHTS ON GAN IN MILLIMETER WAVE 5G FRONT-END MODULES

Echoic Engineering LLC

Document Date: Feb 2021, WP-3 Rev. 1

Author: Kelvin Yuk, PhD

CONTACT INFORMATION

Email: ksyuk@echoicrf.com | **Web:** https://echoicrf.com

5G SYSTEMS AND GAN

GaN has continued to make headways into the advancing state-of-the-art high power RF and microwave applications. A variety of applications arising from 5G/IoT will be the driving force in creating next-gen GaN devices operating at mm-wave frequencies and beyond. The challenges and opportunities for deployment of GaN are identified and discussed here.

The complexity of the cellular infrastructure has evolved from 2G to LTE and now 5G. The expected 5G speeds reaching 1000x that of LTE will not only enhance existing telecom services, but also lay a new infrastructure for emerging applications such as virtual/augmented reality, self-driving cars, the internet of things (IoT) and wearable and implantable devices [1-2].

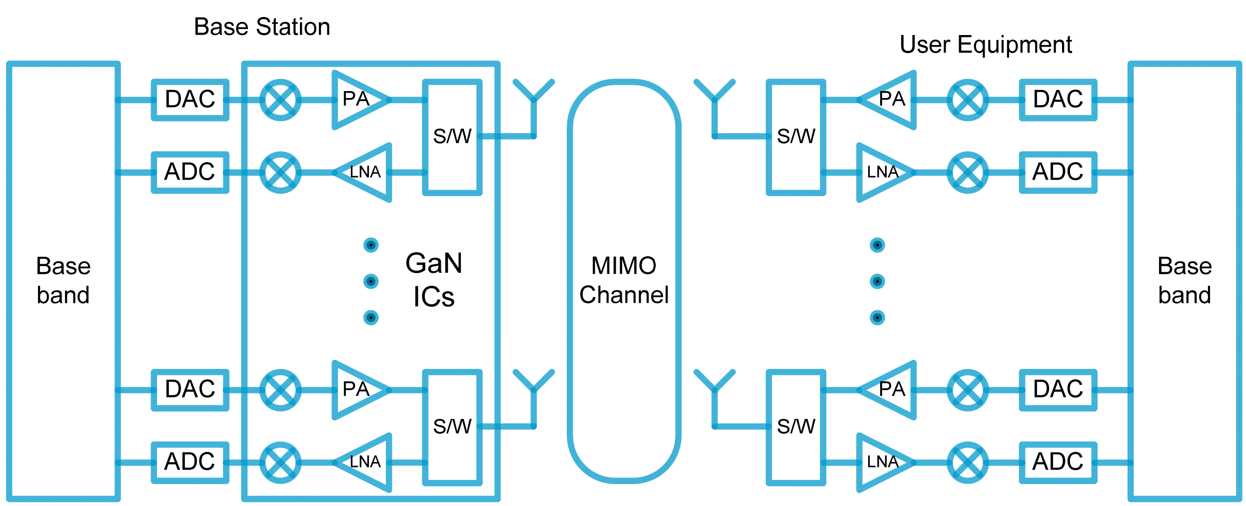


Fig. 1. Digital beamforming architecture for 5G massive MIMO systems.

The 5G architecture will employ multiple input multiple output (MIMO) and beamforming technology to direct signal power for increased over-the-air data rates. A number of demonstration 5G systems achieving more than 3Gb/s have been published in the literature [2-3]. These MIMO architectures will stimulate new design goals on the size and capabilities of the RF transceiver hardware. A block diagram of a digital beamforming 5G massive MIMO architecture is shown in Fig. 1.

Several key directions for 5G have emerged. First, the critical allocation of spectrum will dictate the design and implementation of transceiver hardware. Due to the highly congested sub-6-GHz cellular bands, mm-Wave frequencies are necessary for achieving the desired low-latency, high speed transmission. The FCC has approved of several bands for leading cellular carriers including 28GHz (Verizon, AT&T, T-Mobile), 37GHz and 39GHz (T-Mobile) [4]. Initial development at 28GHz is the most likely but still has significant challenges. While full mm-wave 5G infrastructure is being developed, carriers will first implement sub-6GHz 5G systems employing many of the same MIMO beamforming techniques but at lower, more technologically accessible frequencies. A number of sub-6GHz 5G MIMO systems have been demonstrated at 3.3-4.2 GHz [5].

Massive MIMO beamforming will require a multiplicity of RF circuitry for each antenna element in the phased-array transceiver system. Therefore, size, cost and power density are crucial figures of merit for both the base station and handset architectures. Analog, digital and hybrid beamforming techniques are under consideration. A multiplicity of RF transmit and receive chains will be required as shown in Fig. 1.

GaN technology has been commercially available for several years now and continues to gain momentum for use in a variety of RF and microwave industries. Primarily cultivated as the next-gen PA technology, GaN is being developed for different circuit applications, an activity made possible by the range of foundry offerings as shown in Table I [6-12]. The present state-of-the-art lies within the 0.10um-0.15um channel length range. From Table 1, the foundries equipped to address mm-wave challenges for 5G include [8-12].

Table 1. Commercially available GaN Foundry Services

Foundry	IC Fabrication			Discretes
	Process	Bias (V)	Freq (GHz)	
[6]	0.25um GaN-on-SiC	28-40	18GHz	Y
	0.40um GaN-on-SiC	28, 50	8	
[7]	0.25um GaN-on-Si	N/A	N/A	N
	0.50um GaN-on-Si	N/A	N/A	
	0.50um GaN-on-SiC	N/A	N/A	
[8]	0.20um GaN 4-in	N/A	60GHz	Y
[9]	0.10um	N/A	>70GHz	N
[10]	0.25um GaN-on-SiC 100mm	40V	18GHz	Y
	0.25um GaN-on-SiC 100mm	48V	10GHz	
	0.15um GaN-on-SiC 100mm	28V	40GHz	
	0.50um GaN-on-SiC 100mm	65V	10GHz	
[11]	0.50um GaN-on-SiC 3-in E-mode	N/A	N/A	N
	0.15um GaN-on-SiC 3-in	N/A	Ka-band	
	0.50um GaN-on-SiC 3-in	40V	X-band	
[12]	0.25um GaN-on-SiC	N/A	30GHz	Y

While other technologies are better suited for handsets due to cost, battery voltage and RF power requirements, GaN is a natural candidate for base-station deployment. Continual efforts to customize GaN for lower operating voltages and higher operating frequencies enable the development of switches, LNAs and frequency conversion circuitry. Eventually, it will be possible to integrate the multiplicity of RF chains into a single or several GaN MMICs as highlighted in Fig. 1.

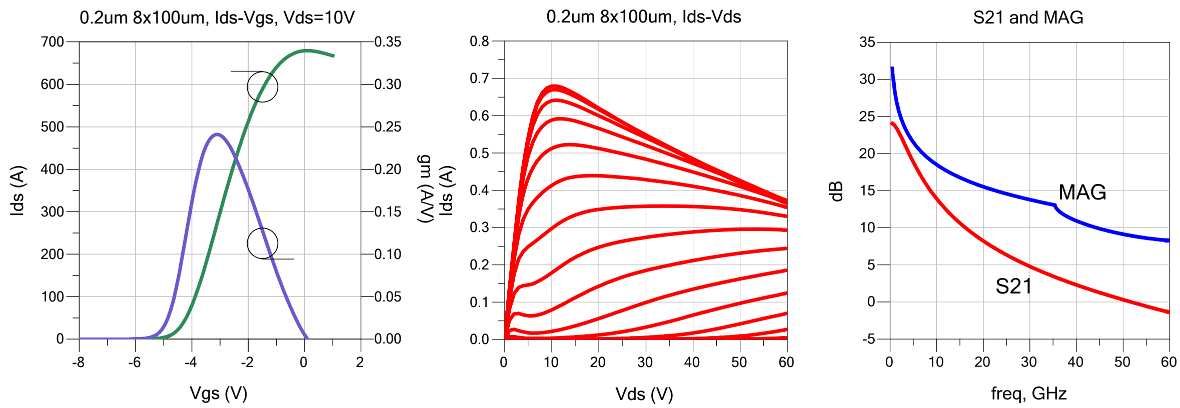
GAN BASE STATION POWER AMPLIFIERS

In MIMO, each antenna is driven by its own PA and therefore it is important to meet the power and linearity requirements while minimizing variation across cells. Development of 5G GaN-based small-cell base station PAs is important for compactness, reduced weight, and low cost while retaining high power and efficiency for ease of deployment.

A thorough understanding of how the unique attributes of GaN such as breakdown voltage, self-heating, trapping, field plate design and transconductance shape impact the operating frequency, power, efficiency (PAE), linearity (harmonics, EVM, ACPR, IIP3, AM-AM, AM-PM), ruggedness, and transient behavior is critical. The desire for high density power will be satisfied by GaN in ways that existing GaAs FET and Si LDMOS solutions cannot. This will require extensive efforts in the modeling of high power devices using dynamic DC and RF techniques [13].

The IV characteristics and maximum available gain (MAG) of a 0.20um GaN 8x100um FET are shown in Fig. 2 to examine the capabilities of presently available GaN technologies for 5G PA design The device exhibits a bell-shaped transconductance (gm) (Fig. 2a) and a significant amount of self-heating (Fig. 2b), both of which are typical of GaN HEMTs. One key research area involves shaping the gm to cater to a specific application. This can include improving PA linearity or PAE depending on the amplifier class. Another research opportunity is in improving the thermal design of the device to reduce self-heating while retaining its high power characteristics.

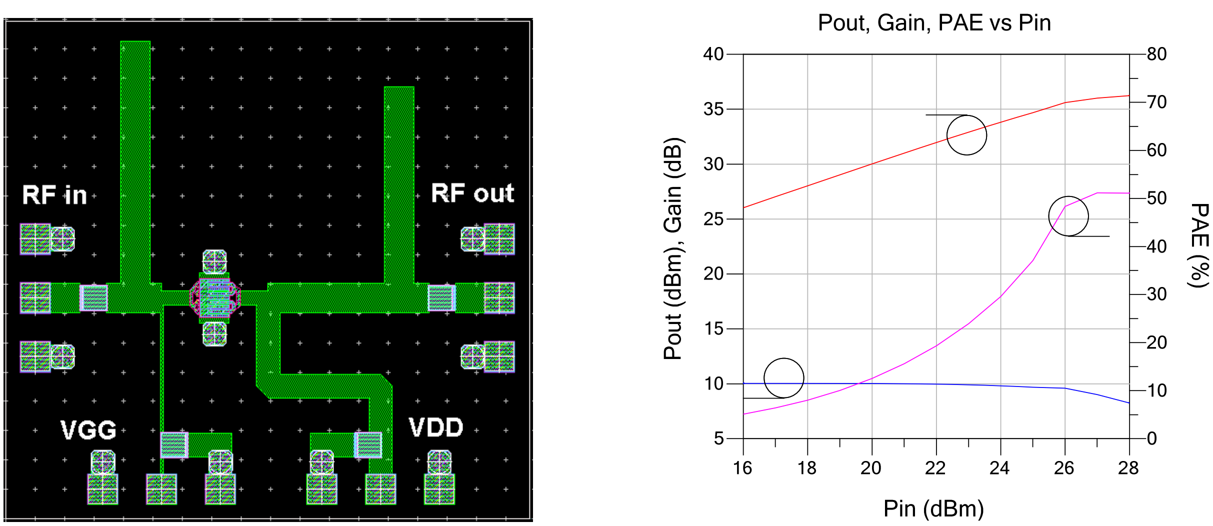
The fT of this particular device is around 51.6GHz, well above the 28GHz operating frequency (Fig. 2c). At 28GHz, S21=5.372dB and MAG=14.091dB. This indicates that there is adequate potential gain at these frequencies. Further extension of the frequency response may involve the reduction of parasitics and field-plate design of the GaN HEMT.



(a) (b) (c)

Fig. 2. Characteristics of a 0.20um GaN 8x100um FET (a) Ids-Vgs and gm-Vgs (b) static Ids-Vds and (b) S21 and MAG.

Considerable research is being conducted to bring GaN into 5G PA design [14]. Much of the GaN PA techniques developed for satellite communications at Ka-band can be leveraged for mm-Wave 5G. A number of GaN HEMT commercial PAs in pre-production will be mature by the time the first 5G standards are drafted [15]. These devices operating at 28GHz provide usable power up to several watts. Presently there is limited availability of GaN HEMTs operating at the 37GHz and 39GHz bands although some research has been done at 32GHz [16]. This identifies a key area of interest for GaN HEMT transistor development in pushing operation beyond 30GHz.



(a) (b)

Fig. 3. 5G PA using a 0.20um GaN 8x100um FET (a) MMIC and (b) Pout, Gain and PAE performance

A Class AB PA MMIC using a single 0.20um GaN 8x100um FET has been designed to investigate the output potential of GaN PAs at 28GHz. The circuit layout is shown in Fig. 3a and the simulated performance is shown in Fig. 3b. This demonstration PA producing a small-signal Gain=10.03dB, and at input P1dB=27dBm produces Pout=36.01dBm with PAE = 51.1% as shown in Fig. 3b. As a PA output stage of a single MIMO transmitter, the design indicates that presently available GaN technology is capable for first generation 5G systems. For base station deployment, this PA can serve as a building block for the Doherty architecture shown in Fig. 4a.

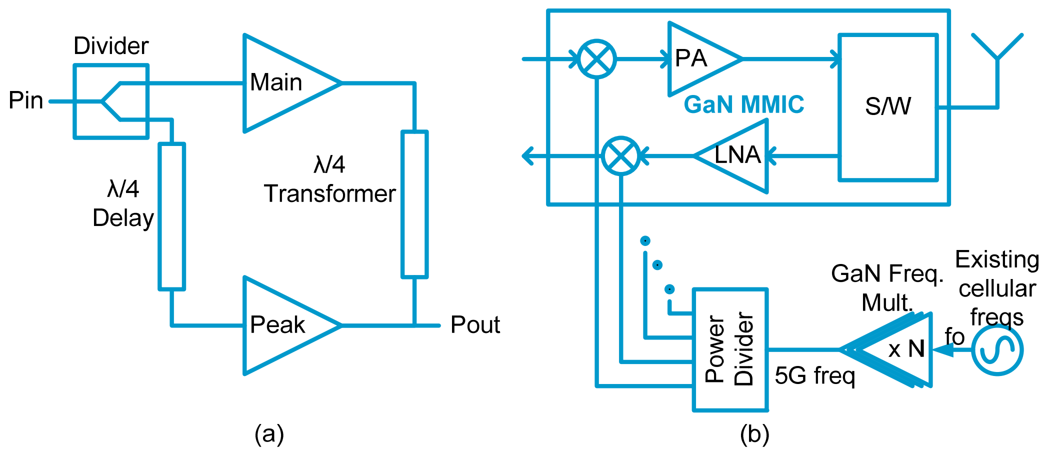


Fig. 4. (a) GaN Doherty PA for base stations and (b) Frequency conversion and distribution using high power GaN frequency multipliers.

A most critical parameter for cellular PAs is linearity, which is frequently characterized as an adjacent channel power ratio (ACPR). However, since 5G waveforms are not yet defined, a suitable general-purpose characterization is the two-tone test. The third-order intermodulation (IM3) products of the 28GHz PA using a 100MHz tone separation is shown in Fig. 5. The GaN PA demonstrates an exceptional third-order intercept point of IIP3=36.6dBm, OIP3=46.6dBm.

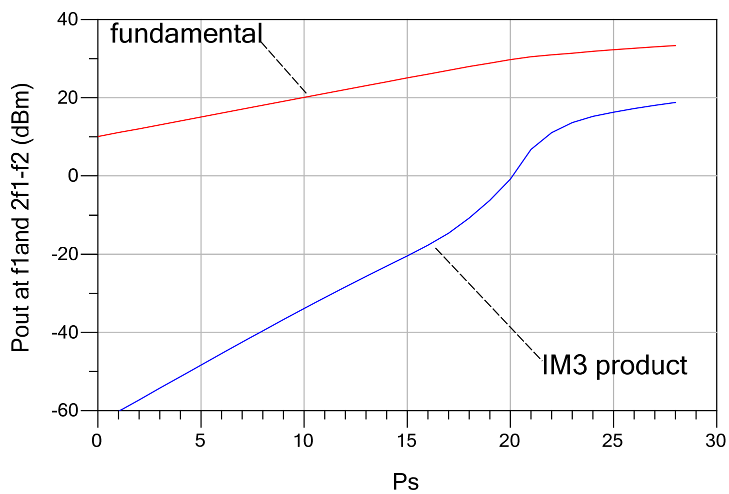


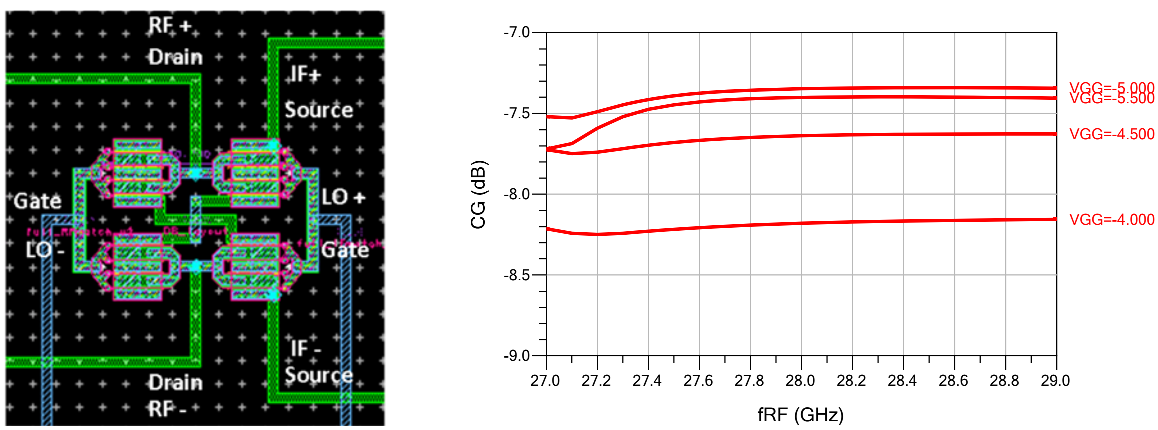
Fig. 5. Two-tone test of 5G PA showing fundamental and lower sideband IM3 products

This demonstration 5G PA illustrates the attainable performance of GaN for 5G systems and highlights the potential areas of improvements on the device level as well as the circuit level.

GAN MIXERS

Another area of research is in developing high performance 5G mixers. Tight integration and mismatch reduction for MIMO can be achieved using an integrated on-chip mixer. Though studies of GaN mixers are limited, some work from the last decade include a variety of single-ended [17], balanced [18] and double-balanced [19] configurations. However, while a few of these mixers have demonstrated operation at Ka-band [18] and still fewer above that [17], most are limited to lower frequencies.

Due to the strict linearity requirements including third-order intermodulation, high-order in-band and out-of-band mixing products, and single-tone harmonics, the double-balanced configuration is preferred over others. It has proven to be superior in terms of linearity and isolation [20]. GaN FET double-balanced mixers operating at 28GHz and above will be an area of focus for the foreseeable future. A double-balanced FET mixer has

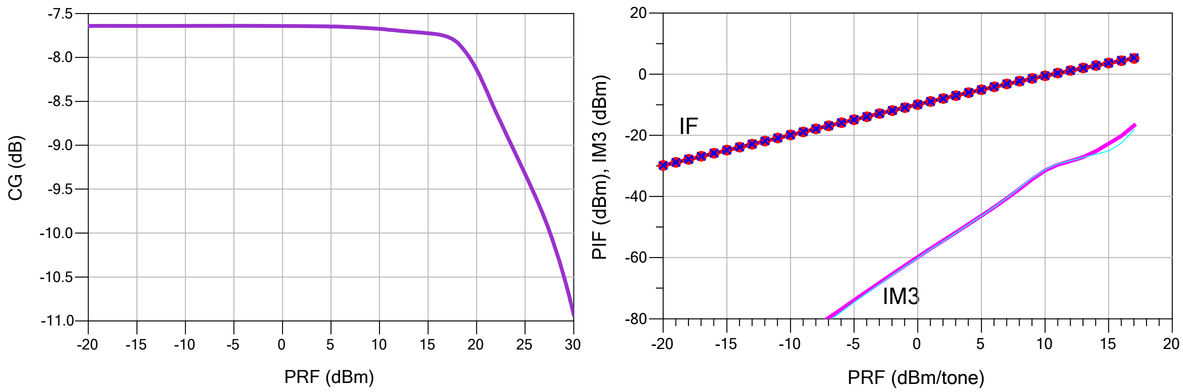


(a) (b)

Fig. 6. Double-balanced mixer quad in a 0.20um GaN HEMT process (a) MMIC and (b) conversion gain over a 2GHz band for various gate bias

To evaluate the performance of a 5G mixer in GaN, a double-balanced quad using 0.20um GaN FETs shown in Fig. 6a is characterized. With fRF=27 to 29GHz and fLO=27GHz, the GaN mixer quad can achieve < 7.7dB conversion loss across band with a VGG=-4.5V as shown in Fig. 6b. Additionally, the linearity and dynamic range is exceptional as shown by the conversion gain (CG) vs power sweep shown in Fig. 7a. The mixer demonstrates an input P1dB=22dBm. For linearity, IM3 products are shown in Fig. 7b, revealing an IIP3=24dBm. The results are achieved without impedance matching. With matching, the performance will improve and the tradeoffs between conversion gain and linearity can be explored.

Mixer conversion gain is highly dependent on the gm shape (Fig. 2a) and quiescent point as seen from Fig. 6b. Since GaN HEMTs are used, an optimal negative gate bias and gate drive level serves to enhance the conversion gain of the mixer. However, it is often preferable for passive mixers to require zero-bias and therefore advantageous to develop GaN which require no external biasing for mixer operation [21].



(a) (b)

Fig. 7. Mixer performance (a) Conversion gain showing 1dB gain compression and (b) Two-tone fundamental and IM3 and products

GAN TX-RX SWITCHES

The Tx-Rx switch (S/W) shown in the Fig. 1 is a critical component which allows for the sharing of a single antenna for both transmit (Tx) and receive (Rx) paths. This is important as antennas typically consume a lot of area. For 5G systems the gain and signal isolation across the module is vital due to the multiplicity of MIMO elements. A GaN front-end solution with integrated switch will allow for a compact design with high power handling capability. There exists some work in GaN switches, but primarily at lower frequencies [22-23]. At 5G frequencies, the properties of GaN which provide low insertion loss and linearity for switch design and can be attributed to the high saturation velocity, breakdown voltage and low parasitics. However challenges remain in reducing charge-trapping and self-heating which will impact switching time and transient response.

In RF switches, the FET is often modeled as a resistive channel in the “on” state and a capacitive channel in the “off” state [24]. A goal of GaN FET design lies in the reduction of Ron and Coff in the on- and off-states, respectively. A lower Ron improves insertion loss in “on” state, while a lower Coff improves the isolation in the “off” state. Widening the device can reduce Ron but this also gives rise to greater parasitics and Coff due to the increased device periphery. Therefore, mitigating the tradeoffs of these two parameters is an active research topic.

Two popular switch configurations suitable for a GaN SPDT switch design are the shunt configuration and series-shunt configuration (Figs. 8a and 8b). The control voltages Vc1 and Vc2 are logical opposites and are used to select which RF path is directed to the ANT port. When RF1 is selected, then RF2 should exhibit a high impedance state and vice-versa when RF2 is selected.

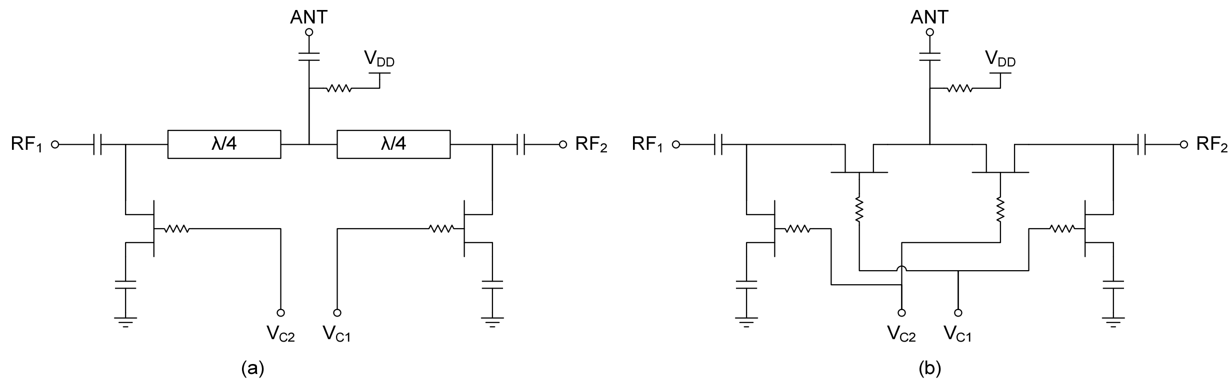


Fig. 8. Tx/Rx Single Pole Double Throw switch using GaN HEMT in (a) shunt configuration (b) series-shunt configuration

A SPDT switch using 0.20um GaN 8x100um FET devices is designed to evaluate the insertion loss, isolation and linearity in a series-shunt configuration. The RF1- and RF2-to-ANT paths have return loss of 24.96dB in the ON state and 1.764 in the OFF state at 28GHz (Fig. 9a). The return loss is better than 12dB from 26-30GHz for wideband operation. The insertion loss of the RF1- and RF2-to-ANT paths is 1.45dB for the ON path and -40.57dB for the OFF path (Fig. 9b). Furthermore, there is less than <1.9dB insertion loss of the ON path and >31dB isolation of the OFF path from 26-30GHz. For both switch states, the RF1-to-RF2 isolation of 41.503dB is achieved at 28GHz as shown in Fig. 9c. This isolation is > 32dB is maintained from 26-30GHz.

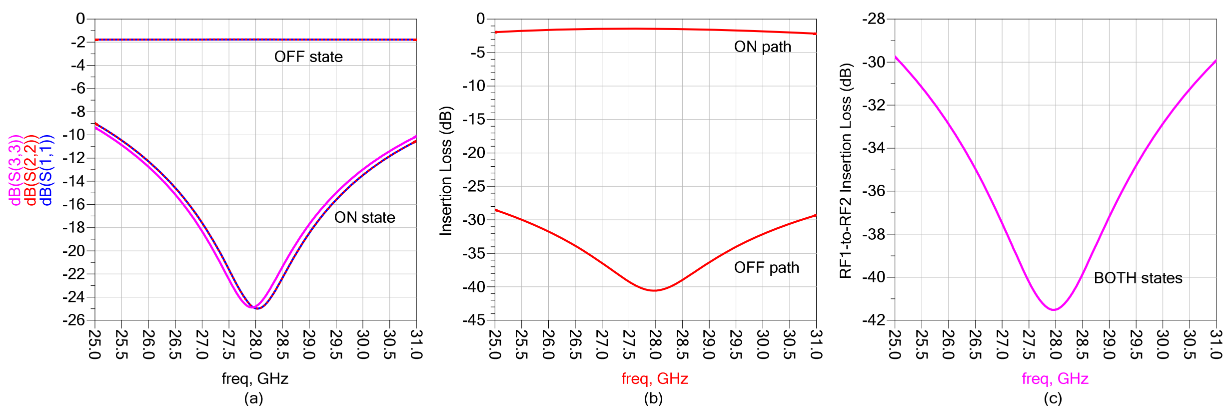
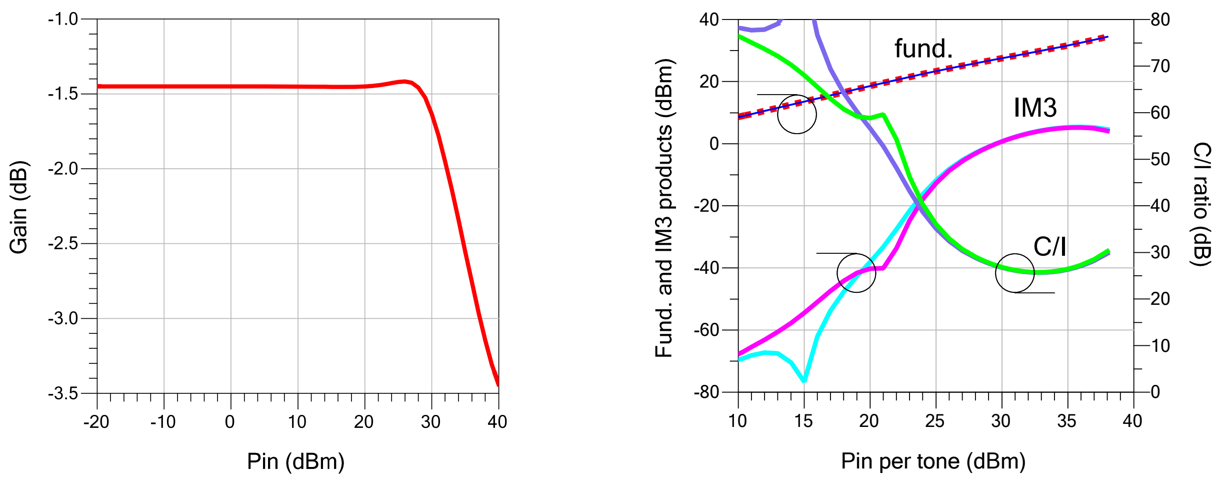


Fig. 9. 5G SPDT series-shunt switch using GaN 8x100um HEMTs (a) return loss (b) insertion loss of ON/OFF states and (c) RF1-to-RF2 isolation

Another key performance trait is the switch linearity, which can be measured using single-tone and two-tone power sweeps. At 28GHz, the 1dB gain compression occurs at input P1dB=34dBm as shown in Fig. 10a.

The two-tone IM3 products and C/I ratio are shown in Fig. 10b. The switch has good linearity with a minimum C/I=25.6dB at Pin=33dBm per tone.

Commercially available products using competing technologies like pHEMT and SOI set the benchmarks for GaN switch performance [25-26]. The performance described here exceeds the performance of [25] which provides an insertion loss of 2.4dB, isolation of 34dB, return loss of 17dB (ON state) and 8dB (OFF state) and input P1db=23dBm at 28GHz.



(a) (b)

Fig. 10. GaN SPDT switch at 28GHz (a) single-tone gain compression and (b) two-tone IM3 products and C/I.

GAN FREQUENCY SYNTHESIS

The number of antenna elements in 5G MIMO systems will increase tremendously. Present demonstrations of the technology have employed 32 or more [14]. With the increased number of transmitters, new challenges in accurately generating and distributing coherent local oscillator power will arise. One direct way of addressing these issues is to amplify the local oscillator power using an amplifier. However, since 5G carrier signals will initially start in the sub-6GHz range, compatibility with lower frequency cellular carrier bands ranging from GSM850/900 to DCS/PCS to LTE frequencies is a necessity.

Therefore, a solution to MIMO power distribution and the compatibility with lower frequency carriers may be solved using high power frequency multiplication to provide adequate power at the desired frequencies. Eventually the same techniques might be applied for generation of the mm-wave 5G carrier.

The dual functionality of high frequency and high power operation can be achieved using high power GaN frequency multipliers which can be accurately distributed using a passive network as shown in Fig. 4b. Nonlinear techniques investigating GaN devices have been developed since the first commercially available

GaN devices [27]. Frequency multiplication allows GaN devices to provide power at above fT using harmonic enhancement techniques.

RESEARCH POTENTIAL AND FURTHER INQUIRIES

A wide range of research opportunity for 5G using GaN lay within new technology development, application-specific device design, device modeling and circuit design. The maturation of GaN is set to converge with the rise of 5G. Therefore it is critical to investigate the viability of GaN prior to the commercial release of 5G standards to gain a market advantage.

Echoic Engineering is actively seeking collaboration in the areas of GaN for 5G. Please contact us at www.echoicrf.com or by email at ksyuk@echoicrf.com.

REFERENCES

[1] Ericsson, Stockholm, Sweden, "5G systems," 2017. [Online]. Available: https://www.ericsson.com/res/docs/whitepapers/wp-5g-systems.pdf

[2] J. Gozalvez, "Samsung Electronics Sets 5G Speed Record at 7.5 Gb/s," IEEE Vehicular Technology Magazine, Feb 2015, pp. 12-16.

[3] B. Sadhu, Y. Tousi, J. Hallin et al., "A 28GHz 32-Element Phased-Array Transceiver IC with Concurrent Dual Polarized Beams and 1.4 Degree Beam-Steering Resolution for 5G Communication," 2017 IEEE Solid-State Circuits Conference, Feb 2017.

[4] 5gamericas, Bellevue, WA, "5G Spectrum Recommendations," 2015. [Online]. Available: http://www.5gamericas.org/files/6514/3930/9262/4G_Americas_5G_Spectrum_Recommendations_White_Paper.pdf

[5] D. Goovaerts, "Intel Unveils 5G Modem with Support for Sub-6 GHz, 28 GHz at CES," [Online]. Available: https://www.wirelessweek.com/news/2017/01/intel-unveils-5g-modem-support-sub-6-ghz-28-ghz-ces

[6] Wolfspeed, "GaN HEMT MMICs," Accessed April 2017. [Online]. Available: http://www.wolfspeed.com/rf/foundry-services/gan-hemt-mmic

[7] Global Comm. Semi., "GaAs & GaN RF Technologies," Accessed April 2017. [Online]. Available: http://www.gcsincorp.com/dedicated_pure-play_wafer_foundry/GaAs%20&%20GaN%20RF%20Technologies.php

[8] Northrop Grumman Corp., "Gallium Nitride (GaN) HEMT for High-Power, High-Frequency Electronics," Accessed April 2017. [Online]. Available: http://www.northropgrumman.com/BusinessVentures/Microelectronics/Products/Pages/Gallium-Nitride-(GaN)-HEMT.aspx

[9] Ommic, "Technology," Accessed April 2017. [Online]. Available: http://www.ommic.com/site/tech-2

[10] Qorvo, "Gallium Nitride (GaN), GaN: The Industry's Hot Technology," Accessed April 2017. [Online]. Available: http://www.qorvo.com/innovation/technology/gan

[11] National Research Council Canada, "GaN Design Kits," Accessed April 2017. [Online]. Available: http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/gan_design_kit/index.html

[12] UMS, "Foundry Services," Accessed April 2017. [Online]. Available: http://www.ums-gaas.com/telechargement/1606_Brochure_Foundry_2016.pdf

[13] K. S. Yuk, G. R. Branner, and D. J. McQuate, "A Wideband, Multiharmonic Empirical Large-Signal Model for High-Power GaN HEMTs With Self-Heating and Charge-Trapping Effects, IEEE Trans. MTT, vol. 57, no. 12, pp. 3322-3332, Dec. 2009.

[14] Y.-S. Noh, Y.-H. Choi, I. Yom, "Ka-band GaN power amplifier MMIC chipset for satellite and 5G cellular communications," 2015 IEEE 4th Asia-Pacific Conference on Antennas and Propagation (APCAP), June 2015.

[15] Northrop Grumman, West Falls Church, VA , "APN228 27-31 GHz GaN Power Amplifier Datasheet Revision: April 2015," Apr. 2015. [Online]. Available: http://www.northropgrumman.com/BusinessVentures/Microelectronics/Products/Documents/pageDocs/APN228rev0415.pdf

[16] M. Micovic; D. F. Brown; D. Regan; J. Wong; Y. Tang; F. Herrault; D. Santos; S. D. Burnham; J. Tai; E. Prophet; I. Khalaf; C. McGuire; H. Bracamontes; H. Fung; A. K. Kurdoghlian; A. Schmitz, “High frequency GaN HEMTs for RF MMIC applications,” 2016 IEEE International Electron Devices Meeting (IEDM), Dec. 2016.

[17] I. Kallfass, G. Eren, R. Weber, S. Wagner, D. Schwantuschke, R. Quay and O. Ambacher, "High linearity active GaN-HEMT down-converter MMIC for E-band radar applications," 2014 Euro. Microw. Int. Circ. Conf., Oct. 2014, pp. 128-131.

[18] M-N. Do, M. Seelmann-Eggebert, R. Quay, D. Langrez, J-L. Cazaux, "AlGaN/GaN mixer MMICs, and RF front-end receivers for C-, Ku-, and Ka-band space applications," 2010 Euro. Microw. Int. Circ. Conf., Sept. 2010, pp. 57-60.

[19] M. van Heijningen, J.A. Hoogland, A.P. de Hek, F.E. van Vliet, “6-12 GHz Double-Balanced Image-Reject Mixer MMIC in 0.25um AlGaN/GaN Technology,” Proc. Of 9th Euro. Microw. Int. Cir. Conf., Oct. 2014.

[20] B. Henderson, E. Camargo, Microwave Mixer Technology and Applications, Artech House, Jul. 2013.

[21] K.-Y. Wong, W. Chen, Q. Zhou and K. J. Chen, “Zero-Bias Mixer Based on AlGaN/GaN Lateral Field-Effect Diodes for High-Temperature Wireless Sensor and RFID Applications,” IEEE. Trans. On Electron Dev., Vol. 56, No. 12, Dec. 2009, pp. 2888-2894.

[22] G. Polli, M. Palomba, S. Colangeli, M. Vittori, E. Limiti, “High power-handling GaN switch for S-band applications,” Integrated Nonlinear Microw. and Millimetre-Wave Circuits Workshop, Apr. 20-21, 2017.

[23] B. Bunz, R. Reber, P. Schuh, M. Oppermann, "High power broadband GaN switch MMICs," Microwave Integrated Circuits Conference (EuMIC), Sept 2015.

[24] R. Cory and D. Fryklund, “Solid State RF/Microwave Switch Technology: Part 2,” Accessed June 2017. [Online]. Available: http://www.skyworksinc.com/downloads/press_room/published_articles/MPD_062009.pdf

[25] Analog Devices, “HMC547LC3 GaAs SPDT Non-reflective Switch, DC-28GHz,” Accessed June 2017. [Online]. Available: http://www.analog.com/media/en/technical-documentation/data-sheets/hmc547lc3.pdf

[26] Peregrine Semiconductor, “PE42525 UltraCMOS SPDT RF Switch, 9kHz-60GHz,” Accessed June 2017. [Online]. Available: http://www.psemi.com/pdf/datasheets/pe42525ds.pdf

[27] K. S. Yuk, G. R. Branner, and C. Wong, “High Power, High Conversion Gain Frequency Doublers using SiC MESFETs and AlGaN/GaN HEMTs,” in IEEE MTT-S Int. Microw. Symp. Dig., pp. 1008-1011, May 2010.