Future Directions for GaN in 5G and Satellite Communications

Invited Paper

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***Abstract*—GaN will play a strong role in advanced RF and microwave applications including 5G and satellite communications. The specifications of these systems will push next-gen GaN devices towards mm-wave operation. The challenges and opportunities for commercial deployment of GaN are identified and a variety of circuit designs are presented. A 5G high-linearity power amplifier MMIC in 0.20um GaN with Pout=36dBm at 51.1% PAE and a Sat-com Ku-band mixer in 0.25um GaN with conversion loss < 10.5dB and IIP3=36.4dBm are demonstrated.**

Keywords—5G, IoT, satellite communications, GaN, HEMT, power amplifier, mixer

I. INTRODUCTION

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 [1-7]. The present state-of-the-art lies within the 0.10um-0.15um channel length range.

TABLE I. COMMERCIALLY AVAILABLE GAN FOUNDRY SERVICES

Ref	Foundry Service			Discretes
	Process	Bias (V)	Freq (GHz)	
[1]	0.25um GaN-on-SiC	28-40	18GHz	Y
	0.40um GaN-on-SiC	28, 50	8	
[2]	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	
[3]	0.20um GaN 4-in	N/A	60GHz	Y
[4]	0.10um	N/A	>70GHz	N
[5]	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	
[6]	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	
[7]	0.25um GaN-on-SiC	N/A	30GHz	Y

Cellular and satellite communications are two vital areas which will fuel the growth in GaN. This work identifies the need for GaN and presents preliminary data illustrating GaN's potential advancement within these two applications. A 28GHz power amplifier (PA) for 5G and a 14.25GHz double-balanced mixer for sat-com are presented. The 5G PA demonstrates an output stage design with high power and PAE from a single transistor. The sat-com mixer illustrates excellent conversion loss, linearity and dynamic range.

II. GAN FOR 5G

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 [8-9].

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 [9-10]. 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.

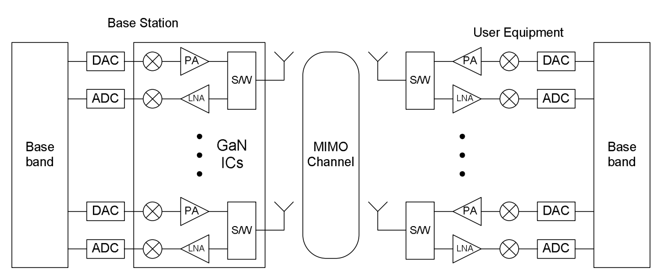

Fig. 1. Digital beamforming architecture for 5G massive MIMO systems.

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

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leading cellular carriers including 28GHz (Verizon, AT&T, T-Mobile), 37GHz and 39GHz (T-Mobile) [11]. Initial development at 28GHz is the most likely but still has significant challenges. From Table I, the foundries equipped to address mm-wave for 5G include [3-7]. 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 [12].

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.

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.

A. GaN base station PAs

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 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 shown in Fig. 2a illustrate the suitability of presently available GaN technologies for 5G PA design. The f_T of this particular device is around 51.6GHz, well above the 28GHz operating frequency (Fig. 2b). At 28GHz, S21=5.372dB and MAG=14.091dB. This indicates that there is adequate potential gain at these frequencies.

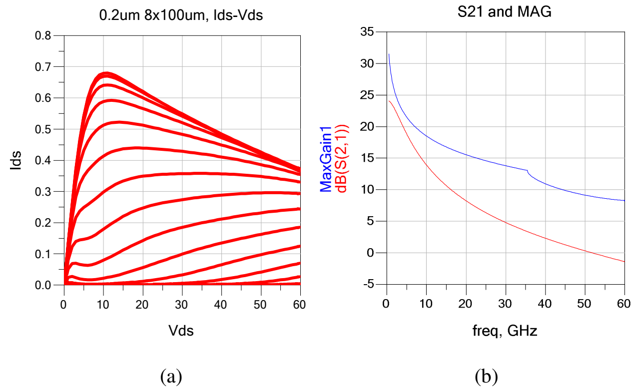

Fig. 2. Characteristics of a 0.20um GaN 8x100um FET (a) static IV and (b) S21 and MAG.

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 are no known commercially available 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.

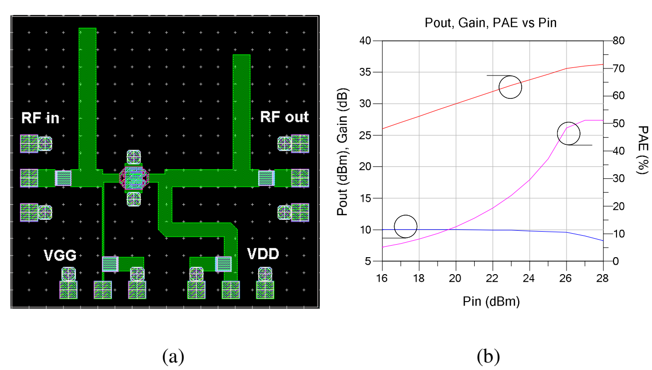

Fig. 3. 5G PA using a 0.20um GaN 8x100um FET (a) MMIC and (b) Pout, Gain and PAE performance

A 28GHz Class AB PA MMIC measuring 1.8mm x 1.7mm using a single 0.20um GaN 8x100um FET device has been designed. 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.

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B. 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 [10]. With the increased number of transmitters, new challenges in accurately generating and distributing coherent local oscillator (LO) power will arise. One direct way of addressing these issues is to amplify the LO power using a PA. However, since 5G carrier signals will initially start in the sub-6GHz range, compatibility with lower frequency cellular bands ranging from GSM850/900 to DCS/PCS to LTE frequencies is necessary.

Therefore, the MIMO signal distribution and compatibility problem may be solved using high power frequency multiplication to provide adequate power at the desired frequencies. Eventually the same techniques might be applied for generating a mm-wave 5G LO signal.

Generation of a high frequency, high power LO signal from a lower frequency reference can be achieved using high power GaN frequency multipliers. The resulting output can then be precisely distributed to each massive MIMO chain using a passive network as shown in Fig. 4b. Nonlinear techniques investigating GaN devices have been developed since the first commercially available GaN devices were available [17]. Frequency multiplication allows GaN devices to provide power at above f_T using harmonic enhancement techniques. The development of GaN technology for high harmonic generation without breaking down is another a possible area of technology development.

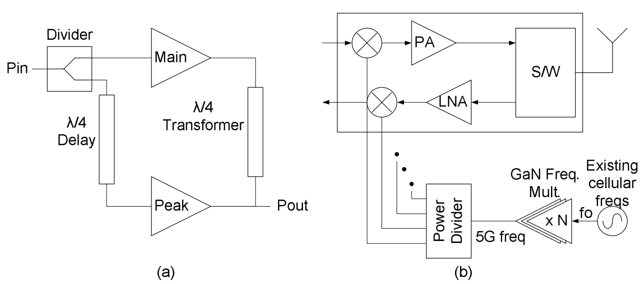


Fig. 4. (a) GaN Doherty PA for base stations and (b) Frequency conversion and distribution using high power GaN frequency multipliers.

III. GAN FOR SATELLITE COMMUNICATIONS

GaN is well positioned for satellite communication subsystems [18]. Existing satellites rely on proven GaAs and TWT technology for much of its RF front-end hardware. However, the maturation and commercial adoption of GaN provides a number of key advances for the space industry. Some of the advantages which earmark GaN as the primary technology for space include high temperature operation, reliability, radiation hardness and >40GHz operation using commercially available processes.

For PAs, the advantages of GaN over TWT amplifiers (TWTAs) and GaAs solid-state PAs (SSPAs) are multi-fold and consequential from the superior electrical characteristics of GaN. These characteristics include high saturation velocity, high breakdown voltage and high thermal conductivity which provide high output power density at microwave frequencies and good reliability under thermal stress. A major cost advantage is also realized by eliminating kW power supplies for TWTAs and cooling hardware for GaAs SSPAs. This reduction of size and weight saves fuel and area on the payload.

GaN's potential for space communication deployment is still largely unrealized. For power devices, the attractiveness of a compact, lightweight form factor is undeniable and creates possibilities for realizing small form factor, micro- and nano-satellites. Although the development of GaN will continue to be driven by its high power RF properties, space qualification of GaN technology as a whole incentivizes its development for use in other RF circuitry. In fact, the potential to realize an entire satellite receiver front-end using GaN clearly illustrates the advantages of higher integration and lower cost [18].

One potential avenue for GaN development is in the mixer. Although, studies of GaN mixers are limited, some work from the last decade include a variety of single-ended [19], balanced [20] and double-balanced [21] configurations. While a few of these mixers have demonstrated operation at Ka-band [20] and still fewer above that [19], 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 been proven to be superior in terms of linearity and isolation [22]. However, there is not much work which demonstrates GaN double-balanced mixers operating into Ka-band. From the literature, one example of particular interest is an X-Band mixer with 1-2GHz IF frequency implemented using 2x75um FETs in 0.25um GaN technology [21].

The mixers in presently deployed satellites use a double-balanced topology consisting of four discrete GaAs diodes in a quad and matched on a ceramic substrate. The use of discrete diodes creates other issues such as mismatch and increased size. Therefore, tighter integration and elimination of mismatch can also be achieved if a single GaN MMIC solution is employed.

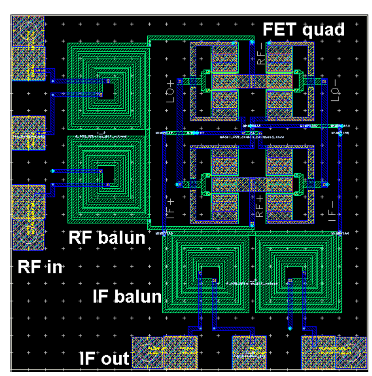
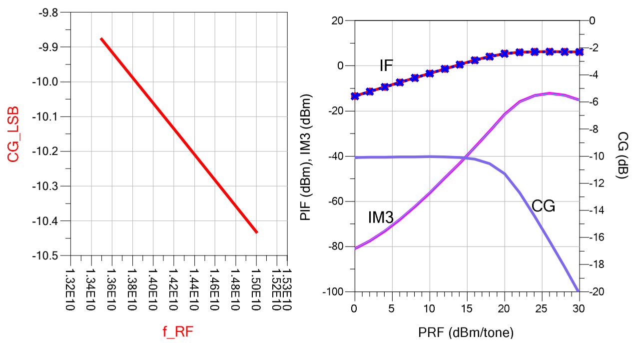


Fig. 5. Double-balanced mixer MMIC in a 0.25um GaN HEMT process.

A double-balanced Ku-band mixer MMIC using 0.25um GaN FETs is designed and shown in Fig. 5. This 1mm x 1mm MMIC consists of Marchand planar baluns for RF input and IF output and a FET-based mixer quad as similarly done in [21]. With an RF input frequency range of 14.0 to 14.5GHz and f_{LO}=1.75GHz, the GaN mixer is able to achieve < 10.5dB conversion loss across band as shown in Fig. 6a. The results are achieved without impedance matching. With matching, the performance will improve even more. Additionally, the linearity and dynamic range performance of the mixer is exceptional. The Pout, IM3 and conversion gain (CG) of the mixer is shown in Fig. 6b and demonstrates an input P1dB=19.5dBm and an IIP3=36.4dBm.



(a) (b)

Fig. 6. Ku-band mixer simulated (a) conversion gain over frequency and (b) IF output, IM3 and conversion gain (showing P1dB) at f_{RF}=14.25GHz.

IV. Conclusion

This work presents applications of GaN in the forthcoming 5G frequency standard and in existing satellite communications systems. As GaN technology continues to improve, the potential for delivering performance in the Ku- and Ka-band for commercial systems will become the main driving point for its adoption. This paper has investigated several circuit designs using a PA and mixer which demonstrate impressive microwave performance from current GaN technologies.

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