Multi-Decade GaN HEMT Cascode-Distributed Power Amplifier
with baseband Performance

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Abstract — This paper reports on multi-decade bandwidth GaN HEMT Cascode-distributed power amplifier designs which achieve performance from base-band to over 20 GHz. The GaN MMICs are based on a 0.2um AlGaN/GaN low noise T-gate HEMT technology with an $f_T \sim 75$ GHz. To increase the MMIC power capability of this low noise GaN technology, a cascode DA design approach was employed which can operate at twice the recommended Vds voltage. The resulting amplifiers achieve 1-4 Watts of saturated CW power from 100MHz to over 20GHz at an operating voltage of 30V. Typical OIP3 $> 40$ dBm and NF of 3 dB were also achieved. Compared to equivalent designs in a similar 0.15um GaAs PHEMT low noise technology fabricated in the same foundry, these multi-decade GaN HEMT MMIC DAs obtain 6 dB higher output power and 5.8-6.6dB higher OIP3 while achieving comparable gain, noise figure, and bandwidth. These are believed to be the first multi-decade GaN power distributed amplifiers that have been demonstrated and can enable future ultra-wideband frequency agile and software defined radio systems that require baseband to microwave frequency operation.

Index Terms — Distributed Amplifier, GaN HEMT, Low Noise Amplifier (LNA), Power Amplifier (PA), Cascode, GaAs PHEMT.

I. INTRODUCTION

Wide band, high dynamic range GaN HEMT MMICs can enable advanced ultra-wideband agile and software reconfigurable communication links. These future systems will require higher device linear power efficiency, wider bandwidth of operation, and lower noise with greater sensitivity. These key front-end semiconductor technology characteristics can ultimately result in higher data rates, greater spectral efficiency, and longer link reach systems. For microwave and millimeter-wave applications, GaN HEMT can enhance the present capability of GaAs PHEMT technology in regards to these enabling performance parameters. The wide band-gap (high breakdown voltage), high electron mobility, and good thermal conductivity of GaN, allows GaN HEMT to achieve comparable bandwidth, similar noise, but operate at higher voltages with significant improvements its output power and linearity. This makes GaN HEMT attractive as a new technology source for building wide dynamic range microwave front-end


d| REF | Author | Circuit Topology | Technology | BDV(V) | $f_T$ (GHz) | Small-Signal BW (GHz) | Gain (dB) | Pout (Watts) | PAE (%) | IP3 (dBm) | Operating Voltage (V) |
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</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>Green, et.al.</td>
<td>Cascode NDPA</td>
<td>0.3um GaN HEMT</td>
<td>-</td>
<td>-</td>
<td>DC-8 (S12 = -5dB below 5GHz)</td>
<td>15</td>
<td>3-6</td>
<td>13-31</td>
<td>43</td>
<td>25</td>
</tr>
<tr>
<td>[2]</td>
<td>Meharry, et.al.</td>
<td>2-stage Power-Combined NDPA</td>
<td>0.15um GaAs PHEMT</td>
<td>16</td>
<td>-</td>
<td>4-18</td>
<td>20</td>
<td>4.3</td>
<td>23</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>[3]</td>
<td>Gassmann, et.al.</td>
<td>1-stage Lange Balanced NDPA</td>
<td>0.15um GaN PHEMT</td>
<td>60</td>
<td>-</td>
<td>4-18</td>
<td>10.4</td>
<td>4.4 (3.2 avg.)</td>
<td>15.6</td>
<td>-</td>
<td>35</td>
</tr>
<tr>
<td>[4]</td>
<td>Campbell, et.al.</td>
<td>NDPA</td>
<td>0.25um GaN HEMT</td>
<td>-</td>
<td>45-50</td>
<td>1-18</td>
<td>10.4</td>
<td>6.9 (4.35 avg.)</td>
<td>32 (20.6)</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>[This Work]</td>
<td>Cascode DA</td>
<td>0.2um T-gate GaN HEMT</td>
<td>-</td>
<td>60</td>
<td>1.5-17</td>
<td>13</td>
<td>9-15</td>
<td>20-38</td>
<td>-</td>
<td>30</td>
<td></td>
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<tr>
<td></td>
<td>Capacitive-coupled DA</td>
<td>0.2um T-gate GaN HEMT</td>
<td>&gt; 60</td>
<td>75</td>
<td>DC-24</td>
<td>15</td>
<td>1-3</td>
<td>10-15 (~25-30 @ baseband)</td>
<td>40.9</td>
<td>30</td>
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<td></td>
<td></td>
<td></td>
<td>DC-20</td>
<td>12</td>
<td>1-4</td>
<td>10-15 (~25-30 @ baseband)</td>
<td>42.6</td>
<td>30</td>
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</tbody>
</table>
components. For ultimate agility, it is desirable to encompass multi-decade frequency operation from baseband to high microwave frequencies, and this is what GaN can offer when combined with a distributed amplifier design.

Several of the recently published GaN HEMT MMIC distributed amplifiers given in Table 1 [1-4] have focused on demonstrating high power bandwidth using the non-uniformly distributed power amplifier (NDPA) topology [5]. This topology improves the PAE of the distributed amplifier design by eliminating the drain termination resistor and optimizing the output power load impedance introduced to each of the transistor sections. However, omission of the output drain termination will severely degrade the low frequency output return-loss match, limiting its practical low frequency operation to above 1 GHz.

In this work, we demonstrate the first GaN power distributed amplifiers that achieve practical multi-decade performance down to 100 MHz and up through 20 GHz. Cascode device cells are used to increase the device supply operation from 15V to 30V which is twice the practical recommended Vds voltage of a single device for this low noise T-gate millimeter-wave GaN HEMT technology. The result is improved MMIC power capability from a low noise process. To further enhance the power-bandwidth, a capacitively-coupled distributed amplifier topology [6] is also demonstrated with a unique baseband performance capability using an all pass coupling network.

II. GaN MMIC DESIGN

The MMICs were fabricated using NGST’s low noise 0.2um T-gate AlGaN/GaN HEMT process technology. The process is optimized for low-noise microwave & millimeter-wave applications. The AlGaN/GaN material is grown on a 3-inch semi-insulating SiC substrate formed by metal organic chemical vapor deposition (MOCVD). Room temperature measurements show a typical 2-DEG of 1.2x10^13cm^-2 and a mobility of 1600cm^2/V-s. HEMT devices were fabricated with a 0.2-um T-gate, 2-um source-to-drain spacing, and 750Å SiN passivation. The Peak transconductance calculated from the DC transfer curve and cutoff frequency (fT) extracted from s-parameters are 285mS/mm and 75GHz, respectively. The maximum oscillation frequency (Fmax) is greater than 120 GHz. Typical pulsed I-V curves measured at a quiescent Vds of 20 V and a Vgs of -8V are shown in figure 1. A BVdg > 60V is obtained for these HEMTs. Although the GaN HEMT devices can achieve high DC operating voltages, the recommended Vds in a practical application may range from 10-15V for circuit robustness. In order to improve the power MMIC capability, cascode devices have been applied in the distributed amplifiers of this work.

Figure 2 and 3 show the schematics of both the conventional cascode and capacitively-coupled cascode distributed PA designs. The conventional design is a 9 section cascode distributed amplifier with HEMT device sizes of 200um width for both transistors of the cascode. With a quiescent Vds of 15V for each device, a supply voltage of 30V may be used. The nominal design bias current density is ~170 mA/mm. The baseband performance of this topology is set by the finite external off-chip capacitors, Cout_ext and Cin_ext on the drain and gate TLIN terminations, respectively. A NDPA topology which eliminates the use of the drain termination would be limited in low frequency output return-loss match capability, but could be optimized for 10-15% better output efficiency than the conventional distributed amplifier. A technique to improve the power bandwidth capability of the conventional distributed topology is the use of capacitive input coupling with the distributed amplifier [6]. The schematic of our GaN implementation is given in Figure 3. This is similar to the conventional cascode DA of figure 2 except that a capacitive all-pass network is employed on the
gate of each cascode cell in order to provide lower effective input capacitance, higher power bandwidth, and baseband performance capability. Just like the conventional DA, the low frequency capability is set by the external gate and drain termination capacitors. The details of the all-pass coupling network will be given in the conference paper. The capacitive couple network enables this design to use larger 300um gate width cell devices and higher total bias current of 400mA at a more conservative current density of 130mA/mm to improve the linearity and power-bandwidth performance.

Figure 4 shows a photograph of the cascode GaN DA MMIC. The chip size is 3.2x1.5mm². The capacitively coupled cascode DA has a similar layout and is not shown.

III. MEASURED PERFORMANCE

The GaN MMIC DAs were characterized using an on-wafer RF probe system for s-parameters, noise figure, IP3 and output power across the band. Figure 5 and 6 show the s-parameter measurements of the two designs. The conventional cascode design achieves a nominal gain of 16 dB with a 24 GHz bandwidth while the capacitively coupled cascode design obtains 12.5dB gain and a 20 GHz bandwidth. Notice that both achieve excellent return-loss better than 12 dB and on average > 15 dB across their respective bands. Also note that the MMICs achieve flat gain and excellent return-loss performance down below 50 MHz. The slight increase in gain below 2-3 GHz is due to probe parasitic effects as well as on-chip damping resistance.

Figure 7 gives the noise figure measurements of both the power GaN DA designs. The conventional cascode design achieves roughly 4 dB NF or better from 1 GHz to 18 GHz with an average mid-band NF of 3 dB. The capacitively-coupled NF is much higher at around 6 dB from 6-18 GHz. At lower frequencies, the NF ramps up due to the capacitive coupled nature of the all-pass network. This is an inherent trade-off with the capacitive coupled technique. The NFs are within a few tenths of a dB to that obtained with an equivalent design in 0.15um PHEMT which is biased at a lower supply voltage of 8V due to device voltage breakdown constraints.

Figure 8 shows the output IP3 of the conventional and capacitively-coupled (CC) cascode DAs biased at 30V (300mA, 400mA). This indicates that the IP3 linearity of the CC design is improved on average by 2 to 3.5 dB across the broad band over the conventional cascode. The CC design achieves better than 40 dBm IP3 up to 17 GHz with a low frequency IP3 of around 44 dBm at 100MHz. At mid-band (10 GHz) the CC design achieves 42.6dBm while the conventional design achieves 40.8dBm IP3. Compared to equivalent 0.15um PHEMT DA designs which achieve 36 and 35 dBm, these GaN designs obtain 6.6 and 5.8 dB improvements in linearity by operating at 30V versus 8V.

Finally CW output power capability at 30V was measured at RF DIE probe level. Figure 9 shows the Psat and P1dB of the
In this work, we reveal for the first time multi-decade performance of GaN power distributed amplifiers using both conventional and capacitively coupled DA topologies. To our knowledge, baseband performance < 1 GHz has not been demonstrated in previous GaN DA works. Cascode devices were utilized to obtain robust power performance from a low noise millimeter-wave GaN HEMT process and demonstrated conventional cascode DA. It achieves a Psat between 1-3 watts across the 100MHz-20GHz band. The PAE is between 10-15% above 2 GHz and 25-30% at baseband. The P1dB is about 2-5 dB lower than Psat which may indicate thermal limitations are softening the compression of the devices (soft I-V knee). Figure 10 shows the Psat and P1dB of the CC cascode PA which indicates a relatively higher Psat range of ~1-4Watts up to 18GHz and a PAE ~ 10-15%. At baseband the PA achieves > 4Watts with a PAE of ~25-30%. The P1dB of the CC cascode design is only 1.5-2.5 dB lower than Psat which may indicate thermal limitations are softening the compression of the devices (soft I-V knee). Finally Table 2 gives a summary of the GaN HEMT distributed PAs and how they compare to equivalent designs in a 0.15um PHEMT operated at a lower supply voltage.

![Figure 9 – Psat, P1dB of the conventional design at 30V.](image)

**IV. Conclusion**

In this work, we reveal for the first time multi-decade performance of GaN power distributed amplifiers using both conventional and capacitively coupled DA topologies. To our knowledge, baseband performance < 1 GHz has not been demonstrated in previous GaN DA works. Cascode devices were utilized to obtain robust power performance from a low noise millimeter-wave GaN HEMT process and demonstrated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
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<tbody>
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<td>Technology</td>
<td>0.2um GaN HEMT</td>
<td>0.15um GaAs PHEMT</td>
</tr>
<tr>
<td>Supply Voltage V</td>
<td>&gt; 60</td>
<td>9.0</td>
</tr>
<tr>
<td>Circuit Type</td>
<td>Cascode DA</td>
<td>CC Cascode DA</td>
</tr>
<tr>
<td>Bandwidth GHz</td>
<td>DC-24</td>
<td>DC-20</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>21.0</td>
<td>12.5</td>
</tr>
<tr>
<td>P1dB (dB)</td>
<td>24.0</td>
<td>25.5</td>
</tr>
<tr>
<td>P1dB (dBm)</td>
<td>32.3</td>
<td>32.5</td>
</tr>
<tr>
<td>Supply Voltage V</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Supply Current mA</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Multi-Watt Wideband MMICs in GaN and GaAs, 2007 IEEE MTT Digest, Honolulu, Hawaii, June, pp. 631-634.</td>
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The authors wish to acknowledge the key contribution of Tony Sellas (RFMD) and Richard To (NGST) for on-wafer RF characterization, and the support and assistance of Curtis Kitani, B. Basyuk, and J. Johnson.

6 dB power and IP3 improvements over GaAs PHEMT equivalent MMIC designs while achieving similar NF, BW, and gain. These high linear-power multi-decade GaN MMIC DA approaches can enable future ultra-wideband frequency agile and software defined radio architectures operating from baseband to 20 GHz.

**Acknowledgement**

The authors wish to acknowledge the key contribution of Tony Sellas (RFMD) and Richard To (NGST) for on-wafer RF characterization, and the support and assistance of Curtis Kitani, B. Basyuk, and J. Johnson.

**REFERENCES**


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