Abstract—We will discuss some design insights on broadband linear and highly-efficient medium-power power amplifiers (PA) for millimeter-wave (mm-Wave) 5G applications. These broadband mm-Wave PAs are targeted to cover most of the key 5G FR2 band (i.e., 24.25 to 43.5 GHz), and support 5G NR modulated broadband signals with high peak-to-average-power-ratio (PAPR). For example, they can operate at both 28 and 37 GHz, with 3dB bandwidth of ~20 GHz or greater with good linearity and power-added-efficiency (PAE). We will present our mm-Wave PA designed in advanced 40 nm GaN technology as an example, and compare its performance with other state-of-the-art broadband 5G mm-Wave PAs designed in CMOS and SiGe BiCMOS as reported in the literature. These prototype medium-power PAs reveal performance trade-offs on $P_{\text{OUT}}$, linearity, PAE and bandwidth, depending on the selection of PA topologies (i.e., Doherty, differential, stacked), device technologies (III-V vs. silicon), biasing schemes and matching network, etc. Measurement data using 5G NR 900 MHz signal with 256 QAM modulation suggests our GaN PA can achieve good linearity with EVM < 5% at $P_{\text{OUT, Linear}} > 10$ dBm for both 28 and 38 GHz simultaneously without predistortion, and the PA also achieves max. PAE > 30% for CW operation.

Keywords — 5G, CMOS, CMOS-SOI, GaN, millimeter-wave (mm-Wave), Phased-array, Power Amplifier (PA), SiGe.

I. INTRODUCTION

The 5G (5th Generation) mobile communication will move beyond the data-rate limitations of the traditional sub-6 GHz networks by utilizing the millimetre-wave (mm-Wave) channels, enabling 10 Gb/s mobile communications in urban areas for eMBB (enhanced Mobile Broadband) applications, as well as mMTC (massive machine type communication) and URLLC (ultra-reliable machine type communication). Energy-efficient and high-performing mm-Wave transceivers and FEM (front-end module) with Watt-level $P_{\text{OUT}}$ are needed for base-station (BS) equipment, while for 5G user equipment (UE) and femto/picocells, the PA’s output $P_{\text{OUT}}$ will only need to be at the 10-100 mW range [1,2]. For example, Ref. [3] is one of the earliest reported fully integrated 28 GHz FEM IC, which is designed in a 0.15-μm GaAs pHEMT (pseudomorphic High Electron Mobility Transistor) process and includes a three-stage common-source PA, a three-stage low-noise amplifier (LNA), and a single-pole, double-throw T/R switch. The PA achieves 26 dBm $P_{\text{OUT,1db}}$ on die, and it realizes 30 dBm linear EIRP (equivalent isotropically radiated power) in a four elements array. However, as mentioned, this high $P_{\text{OUT}}$ level is not needed for mm-Wave 5G UE. For example, a 28-32 GHz phased-array SiGe IC with 4 transmit/receive channels each was reported in [4] for 5G, where $P_{\text{OUT}}$ in transmit mode is only 10 dBm at $P_{\text{IN}}$ [3]. Other published work has confirmed the $P_{\text{OUT}}$ spec for each mm-Wave 5G PA with MIMO (multiple-in-multiple-out) antennas can be considerably relaxed vs. their 4G LTE counterparts [4-8]. However, because the mm-Wave 5G PAs are operating at ~x7-15 higher frequencies vs. their sub-6 GHz counterparts, their broadband linearity and PAE may be considerably lower than the 4G PAs, which makes this a very critical barrier to overcome to enable mm-Wave 5G revolution. In addition, it would be highly desirable to have a minimal number of broadband mm-Wave PAs to cover the entire 5G FR2 band (i.e., 24.25 to 52.6 GHz), as this will minimize the number of mm-Wave PA/FEM components to reduce system complexity, size and overall cost [8,9]. Designing narrow-band mm-Wave 5G PAs with peak PA above 30% is already challenging, but it becomes much more difficult to realize broadband PA with max. PAE above 30% across the 5G FR2 bands, not to mention to further maintain good PAE at power back off to support excellent linearity for 5G NR high PAPR signals. Thus, several research teams are investigating how to realize very broadband medium-power mm-Wave PAs that can cover the key 5G FR2 band with outstanding linearity and broadband high PAE. We expect this kind of broadband mm-Wave 5G PA designed in advanced III-V technologies may benefit from high-performance packaging for hybrid silicon/III-V systems to offer superior linearity/PAE/$P_{\text{OUT}}$/breakdown performance trade-offs than the all-silicon solutions. However, the all silicon mm-Wave PA design approach provides excellent integration capability and potential cost advantages and thus may be very attractive for mm-Wave 5G and phased-array applications. In our own mm-Wave GaN PA work to be discussed here, we have picked the broadband PA target design specs of $P_{\text{OUT, sat}} > ~16$ dBm for the key part of 5G FR2 band from 24.25 to 43.5 GHz, and with a max. PAE > 30%.

To see what PA device technologies may be most appropriate for designing these very broadband mm-Wave 5G medium-power PAs, we have plotted data points corresponding to some of literature’s mm-Wave narrowband PAs in Fig. 1 in various device technologies. One can clearly see that the advanced silicon-based PAs can handle our target $P_{\text{OUT}} > 16$ dBm spec, at least for mm-Wave narrowband PAs [2]. For applications where $P_{\text{OUT}}$ needs to be above ~3 to 10 Watts at 15 GHz and above, Fig. 1 indicates that state-of-the-art silicon PAs still have difficulties competing with their III-V counterparts. Note most reported mm-Wave GaN PAs in literature are for high-power defense or aerospace applications, but we will specifically examine broadband GaN PAs for mm-Wave 5G FR2 band at low $P_{\text{OUT}} < 1$W here (i.e., $P_{\text{OUT}} ~ 16$ dBm). The PAs are designed in advanced 40-nm GaN using 5G
NR wideband modulated signals. The GaN PA provides excellent broadband linearity/PAE/\(P_{\text{OUT}}\) trade-off without varying PA’s load impedance nor biasing, and may be attractive for mm-Wave 5G and other phased-array applications.

II. BROADBAND MEDIUM-POWER MM-WAVE GaN PA DESIGN

Our broadband GaN PA is designed using an advanced 40-nm GaN pHEMT process on SiC substrate developed by the Hughes Research Labs (HRL) [10]. Load pull simulations on the 4 x 37.5 \(\mu\)m power device are performed using National Instrument’s (NI’s) AWR Design Environment, where the max. PAE circles from 20 GHz to 50 GHz and the PA’s schematics are shown in Figure 2. A 4 x 37.5 \(\mu\)m device is chosen as it has a good trade-off of high gain, max. PAE and lower optimum load impedance. Optimum load impedances close to 50 \(\Omega\) are important for broadband output matching to realize reasonably high broadband PAE by reducing the frequency dependency of the reactive components. This output matching is also designed using only two components (with a RF choke and a DC block) to achieve broadband performance while minimizing lossy on-chip components to render high PAE. A simplified schematic of a 1-stage fully-monolithic GaN PA using 3rd-order input matching is also shown in Fig. 2 to produce good broadband \(S_{11}\). The post-layout parasitic extracted (PEX) full EM simulations in AXIEM plotted in Fig. 3 suggests that this PA exhibits a rather flat \(S_{21}\) gain of \(~10\) dB across the entire band of interests from 24 to 44 GHz, and both \(S_{11}, S_{22}\) are well-behaving. The large signal performance of the mm-Wave PA is also plotted in Fig. 3, where max. PAE= 34.8% at \(P_{\text{OUT}}=19.5\) dBm is achieved at 35 GHz by simulations, which agrees well with measurement, as will be discussed next.

III. BROADBAND MEDIUM-POWER GaN PA MEASUREMENT

A. Small-Signal Measurement Data

The measured vs. simulated S-parameter results of this GaN PA at \(V_{DD} = 12\) V are plotted in Fig. 4. The measurement shows very good small-signal RF and DC agreement vs. simulation after adjusting the DC biasing point by \(-0.7\) V (a threshold voltage shift) to match the simulated bias current level.

B. Large-Signal Measured Performance - CW

Fig. 5 shows the measured large signal CW (continuous-wave) performance of this GaN PA at 28 GHz with \(V_{DD} = 6\) V and 12 V. At \(V_{DD} = 12\) V, measured PAE of 18.2% is achieved at \(P_{\text{OUT}}=15.2\) dBm. When \(V_{DD}\) is reduced to 6 V, we achieved a max. PAE of 27% at \(P_{\text{OUT}}=14.3\) dBm at 28 GHz. One can see both small-signal & large-signal measurements match very well vs. the PEX full EM simulated results. Due to cable losses and that a mm-Wave broadband
linear PA driver was not available in our test setup, the measured max. PAE did not reach their peaks at $P_{OUT, Sat}$ yet. However, the PA should achieve targeted max. PAE > 30%.

Fig. 5 Large signal CW measurements of the GaN PA at 28 GHz with $V_{DD} = 6V$ (TOP) and $V_{DD} = 12V$ (BOTTOM for $V_{GS} = -1.0V$ at $I_{DS} = 25 mA$.

**C. Large-Signal Testing with Wideband Modulated Input**

The broadband performance of the GaN PA was also investigated with three different wideband modulated signals using (a) 20 MHz 64-QAM 4G LTE, (b) 400 MHz 64-QAM 5G NR, and (3) 9x100 MHz 256-QAM 5G NR at several different mm-Wave frequencies and at both $V_{DD} = 6V$ and 12V. All three signals were clipped to have the same PAPR of 8 dB to compare the effects of signal bandwidth on linearity and performance, while the 9x100 MHz was implemented using CA (carrier aggregation) of 9 100 MHz bands. No additional predistortion has been applied here. Note that the larger BW signals do have some spurs, but this is from the equipment as the signals are created digitally then upconverted. The PA output spectra, ACP (Adjacent Channel Power Ratio), EVM and PAE measurement for 24 GHz and 38 GHz at $V_{DD} = 6V$ are shown in Figs. 6-8 for all three modulated signals. The data indicates that with wider modulated signal BW, the PA's linearity (ACP and EVM) worsens at all frequencies, while increasing the signal frequency also degrades its linearity and PAE. Note when increasing the modulation BW from 20 MHz to 900 MHz (a factor of 45x), we see a sizable degradation in the ACP of 7.3/14.2 dB at 28/38 GHz, respectively, while the calibrated EVM (i.e., removing the intrinsic small EVM from the test setup) only degraded by ~1.5%. Note the reported ACP did not have the test setup intrinsic nonlinearities calibrated out like we did for the EVM data. Using the 400 MHz 64-QAM 5G NR as input, this broadband GaN PA achieves a PAE of 8.1% with $P_{out} = 11.5$ dBm at 24 GHz, while maintaining good ACP +/- of -30.2/-30.0 dBc and EVM of 5.8% (see Figure 6). At 28 GHz this PA has a PAE of 7.3% with ACP +/- of -30.3/-29.4 dBc and EVM of 5.0% and $P_{out,Linear} = 11.0$ dBm.

IV. DISCUSSIONS VS. OTHER BROADBAND MM-WAVE 5G PA

In our literature search of other state-of-the-art broadband medium-power mm-Wave 5G PAs that cover the key 5G FR2 band, Table I shows this GaN PA exhibits top-end linearity at 28 GHz with wideband modulated input signals. For example, this GaN PA exhibits the best EVM of 3.4% and ACP <30.7 dBc at 28 GHz for $P_{OUT} = 10.6$ dBm with 256-QAM 5G NR input of 900 MHz (i.e., 100MHz x9), while also maintaining good linear PAE=6.5% across the entire 18-38 GHz band.
without needing the Doherty-like PA architectures as reported in [8-9]. Note Ref. 9 introduced a state-of-the-art transformer-based low-loss and broadband on-chip Doherty power combiner and a power-dependent Doherty PA uneven-feeding scheme based on a “driver-PA co-design” method. It uses a 9-section varactor-loaded transmission lines with adjustable settings to enable its bandwidth coverage, which setting adjustment may not be realized in real-time and the PA is not likely to be able to cover the entire 24-39 GHz band as well. Therefore, some more research work is still needed to enable these prototype state-of-the broadband linear high-efficiency mm-Wave PAs for practical mm-Wave 5G and other phased array applications.

V. CONCLUSIONS

This paper has reported a design example of a broadband high-efficiency mm-Wave medium-power linear PA in 40-nm GaN. Small and large signal measurements validated that this PA is quite broadband, linear, and efficient, as measured data and PEX EM simulations have corroborated well. We have investigated 3 different types of wideband modulated input signals and showed that the PA performance does not degrade much from 28 to 38 GHz, and it maintains good EVM of < 5.0% as modulated signal BW increases from 20/400 MHz (64-QAM) to 9x100 MHz (256-QAM). This GaN PA has high broadband PAE and among the best linearity (ACP and EVM) when compared to other state-of-the-art broadband mm-Wave 5G PAs, and without needing to vary the PA’s load impedance or matching network or biasing points under various input power, frequencies and modulation conditions. The available test data also demonstrates that this GaN PA achieves the highest peak PAE at 28 GHz among the state-of-the-art broadband linear mm-Wave 5G PAs reported (see Table I). More broadband GaN PA measurement data will be presented in the conference to update the performance values when the PA is driven into saturation.

ACKNOWLEDGMENT

This material is based on research sponsored by Air Force Research Laboratory (AFRL) and Defense Advanced Research Projects Agency (DARPA) under Grant Number FA8650-19-1-7902. The US Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation thereon. We also thank TTU Keh-Shew Lu Regents Chair Endowment and the GlobalFoundries University Program, esp. D. HARE, N. Cahoon, C. Kretzschmar, K. Barnett, A. Joseph, and D. Wang.

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<th>Ref.</th>
<th>Tech.</th>
<th>Design</th>
<th>3-dB BW (GHz)</th>
<th>Freq. (GHz)</th>
<th>Max $P_{\text{OUT, sat}}$ (dBm)</th>
<th>Peak PAE (%)</th>
<th>Gain (dB)</th>
<th>Signal Type</th>
<th>ACP (dBc)</th>
<th>EVM (%)</th>
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<td>15</td>
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<td>37</td>
<td>19.6</td>
<td>21.9</td>
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<td>PAE = 1.8%</td>
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*Note: PA not driven to saturation yet; $P_{\text{OUT}}, P_{\text{OUT, sat}}$, and peak PAE will be higher & updated later with an additional mm-Wave broadband linear PA driver

**Obtained from post-layout parasitics extracted with full EM simulation