# A Highly Efficient Broadband mm-Wave 24-32.5 GHz SiGe PA for Potential 5G Applications

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**We present in this work a highly efficient broadband millimeter-wave power amplifier (mm-wave PA) design in a 90nm SiGe technology for potential 5G applications. The post-layout extraction simulations suggest that the PA achieves broadband power-added efficiency (PAE) >31.4%, gain >8.5 dB, and $P_{OUT,sat}$ >13.3 dBm across 24-32.5 GHz, with peak PAE of 40.2% at 26 GHz. The PA shows good linearity with 16-QAM LTE 250 MHz modulated signal input, obtaining ACLR1 of -38.6/-37.3 dBc at 26 GHz with $P_{OUT,avg}$ of 6.4 dBm. The PA is also robust against variation in bias $V_B$ = 0.83-0.85 V and supply $V_{CC}$ = 1.0-1.4 V and can be applicable toward multi-band 5G applications.**

***Index Terms*** **— 5G, broadband, high-efficiency, millimeter-wave (mm-Wave), power amplifier (PA), SiGe**

## I. INTRODUCTION

In the US alone, the sub-50 GHz mm-wave bands cover 18 GHz bandwidth (BW) from Band 24 (24.25-24.45 GHz) to Band 42 (42-42.5GHz), which makes it desirable for the Fifth Generation (5G) transmitters to provide multi-band and multi-mode broadband operations. Additionally, the mm-wave power amplifiers (mm-wave PAs) can often consume about half of the overall system power budget and also dictate the performance (efficiency, linearity, output power) of the entire transmitter. In order to achieve precise beamsteering, considerably more PAs with lower $P_{OUT}$ requirements are needed to be integrated in the RF front-end modules (FEM) for massive-MIMO (multiple input multiple output) type of 5G systems to be implemented [1]. Therefore, the design of low-cost monolithic broadband and highly efficient mm-wave 5G PAs is very important to enable the realization of low-power and miniaturized mm-wave phased array systems for both commercial 5G and Department of Defense (DoD) applications. It is already fairly difficult to achieve $35^{+}$% peak PAE for narrowband mm-wave PAs; it becomes much more difficult to design a PA to cover the entire 24-42 GHz range while maintaining $35^{+}$% peak PAE. To address all these issues of higher integration, lower cost and highest efficiency with relaxed $P_{OUT}$ requirements, silicon-based mm-wave 5G PAs have become very attractive as they offer good $f_{max}$ and higher integration than III-V based PAs such that all the components of one or multiple FEM (RF switches, PA, low-noise amplifier or LNA, phase-shifters etc.) can all be integrated onto one silicon IC [2-3]. In this work, we present a single stage common-source (CS) broadband PA design that utilizes an advanced 90 nm SiGe BiCMOS 9HP technology from GlobalFoundries. This technology offers peak $f_{max}$ ~370 GHz and has higher breakdown voltages and higher device PAE than their CMOS counterparts. This broadband PA design has been laid out and simulated with post-layout parasitic extraction (PEX), and it has been sent out for fabrication. Because of its broadband high efficiency performance, this PA may be attractive for 5G 24-32.5 GHz multi-band applications.

## II. BROADBAND SIGE PA DESIGN

The proposed PA is designed using HP cbebc HBTs (peak $f_{max}$~370 GHz), and all components, including the RF-choke and I/O matching elements are integrated on chip. A simplified schematic of the PA is shown in Fig. 1. Transistor sizing of 0.1µm x 10µm, m=4 is selected for the design due to its very high peak PAE performance of ~46%. In this PA design, we target to maximize its PAE with a bandwidth coverage of larger than +/- 15% (i.e., 24-32.5 GHz). A 3rd order input matching is adopted for improving its broadband performance, while the output load is designed to match PAE circles from load-pull data, using minimal number of components for max PAE with decent bandwidth. The bias voltages are $V_B$ = 0.84V and $V_{CC}$ = 1.2V.

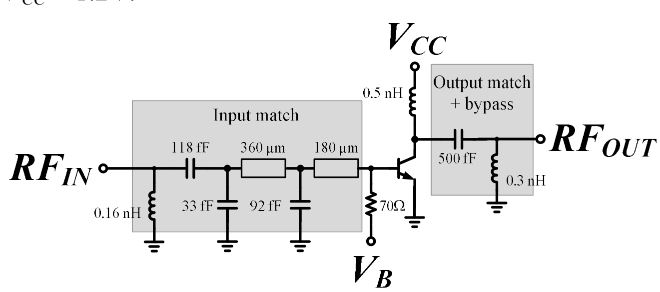


Fig. 1 Simplified schematic of the fully integrated broadband SiGe PA

## III. POST-LAYOUT SIMULATED MM-WAVE PA RESULTS

The PA is carefully laid out, and its layout screenshot is shown in Fig. 2. Post-layout parasitic are extracted in

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Cadence using the R+C+CC option, and simulations are then run extensively to characterize and optimize the PA performance iteratively with its layout modifications. We did not opt to use EM simulated passive network but used the passive models provided by the 9HP design kit. Fig. 3 shows the S-parameter simulation performance with post-layout extraction (PEX). Although the PA achieves >8.5 dB gain from 22-35 GHz, a 3-dB BW of 13 GHz, its PAE remains >31.4% from 24-32.5 GHz, sufficient to cover the entire US 5G bands of Band 24, 25, 28, 29 and 31, respectively. The reasonable broadband performance of the PA is shown across 24-32.5 GHz, and the peak PAE is at 40.2% with $P_{OUT}$ = 12.4 dBm at 26 GHz. Fig. 4 shows the PEX-simulated large-signal performance at 26 GHz. The max PAE varies from 38.8%/12.2 dBm at 24 GHz to 40.2%/12.4 dBm at 26 GHz to 31.4%/11.4 dBm at 32.5 GHz. The gain, max. PAE, and $P_{OUT,sat}$ vs. frequency are shown in Fig. 5, and a summary table of its CW performance is shown in Table I.

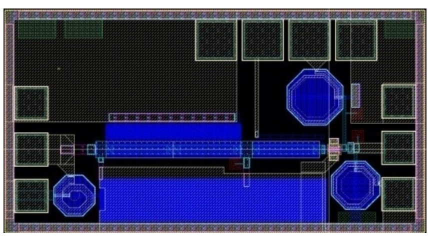

Fig. 2 Layout screenshot of the broadband SiGe PA. The area is 950 μm x 600 μm with pads

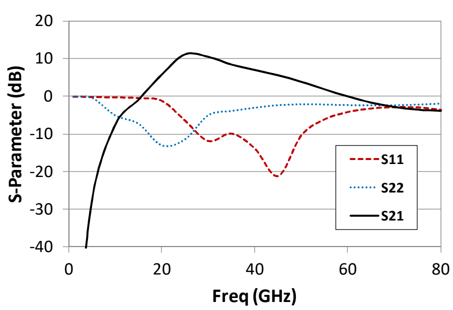


Fig. 3 S-parameter PEX simulation of the broadband SiGe PA

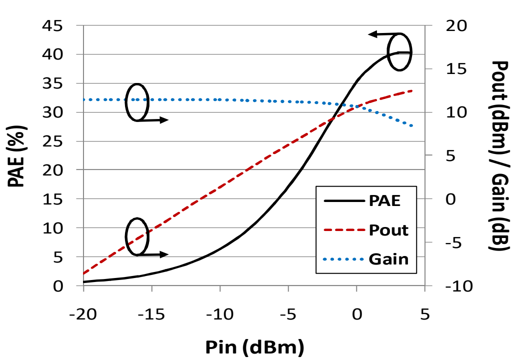


Fig. 4 Large-signal PEX simulation of broadband SiGe PA at 26 GHz

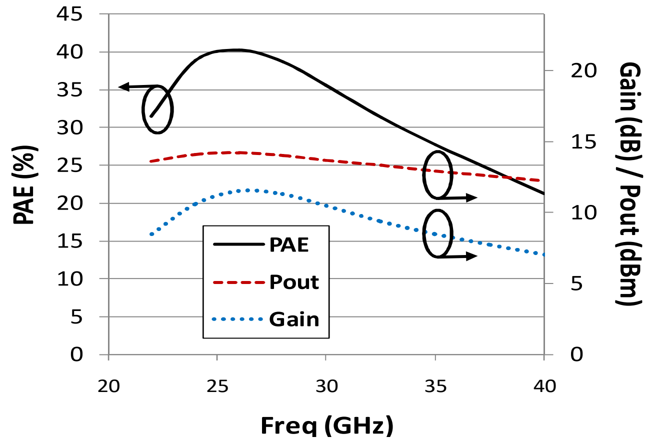


Fig. 5 PAE/gain/$P_{OUT}$ vs. frequency from PEX simulation of the broadband SiGe PA

TABLE I Post-Layout Extracted (PEX) Simulation Performance Summary of the Broadband SiGe PA

| Freq (GHz) | $S_{21}$ (dB) | $S_{11}$ (dB) | $S_{22}$ (dB) | Max PAE (%) | $P_{OUT}$ @ Max PAE (dBm) | $P_{OUT,sat}$ (dBm) |
|---|---|---|---|---|---|---|
| 24 | 10.6 | -4.5 | -15.0 | 38.8 | 12.2 | 14.1 |
| 26 | 11.5 | -9.0 | -9.0 | 40.2 | 12.4 | 14.2 |
| 28 | 11.3 | -13.5 | -6.2 | 38.7 | 12.3 | 14.0 |
| 30 | 10.5 | -11.9 | -5.1 | 35.5 | 11.9 | 13.7 |
| 32.5 | 9.4 | -10.0 | -4.4 | 31.4 | 11.4 | 13.3 |
| 35 | 8.5 | -9.9 | -3.9 | 27.7 | 10.9 | 12.9 |
| 37.5 | 7.7 | -11.1 | -3.5 | 24.4 | 10.5 | 12.6 |
| 40 | 7.0 | -13.9 | -3.1 | 21.3 | 10.0 | 12.2 |

We also need to consider the linearity and robustness of the SiGe PA for 5G applications. Fig. 6 shows the PEX simulation of $S_{21}$ vs. change in $V_{CC}$ supply, and Fig. 7 shows the gain, PAE, and $P_{OUT}$ vs. $V_{CC}$. The broadband $S_{21}$ performance of the PA is shown to be not significantly affected by $V_{CC}$ change, with its large signal gain remains rather flat and peak PAE slightly increases to 41.2% at $V_{CC}$=1.4V. The gain/PAE/$P_{OUT}$ vary by 0.5dB/3.4%/2.2dBm from $V_{CC}$ = 1.0V to $V_{CC}$ = 1.4V for PEX simulations.

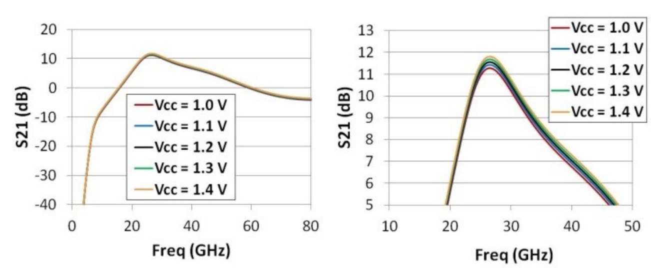


Fig. 6 $S_{21}$ performance for varying $V_{CC}$ from 1.0 V – 1.4 V

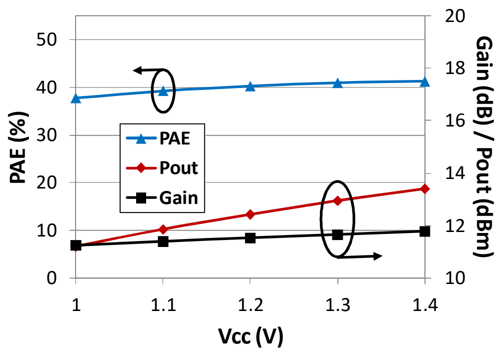


Fig. 7  PAE/gain/$P_{OUT}$ vs. $V_{CC}$ for the broadband SiGe PA

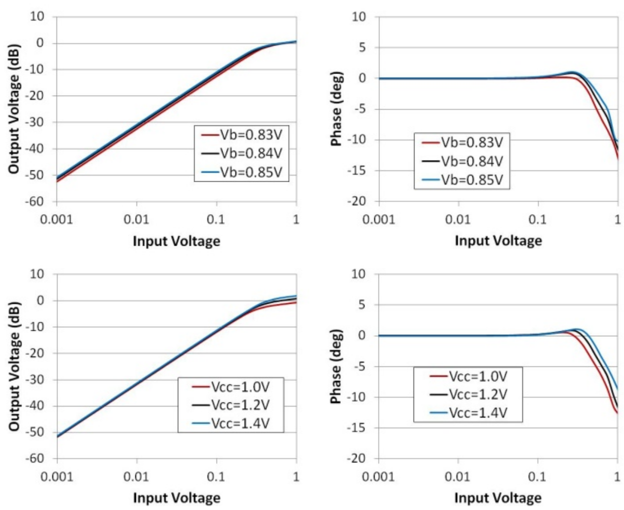


Fig. 8  AM-AM and AM-PM of the broadband PA at 26 GHz vs. varying $V_B$ (TOP) and vs. varying $V_{CC}$ (BOTTOM)

The AM-AM and AM-PM linearity simulations are shown in Fig. 8 vs. varying base bias $V_B$ from 0.83-0.85 V and varying supply $V_{CC}$ from 1.0-1.4 V. These large-signal PEX simulations are done by normalizing the input voltages with the maximum input voltage, and the output voltage is not normalized; both axes are plotted in log scale. One can see changing $V_B$ and $V_{CC}$ in this range has a minimal effect on the AM-AM and AM-PM distortion, and the PA's AM-PM appears small (<5°) at $P_{OUT,1dB}$.

Because the PA linearity and broadband performance appear robust vs. power supply variation, power supply modulation techniques including dynamic supply modulation such as envelope tracking (ET) might be applied to the PA for additional PAE enhancement at power backoff in the future [14]. The performance of the broadband SiGe PA is simulated with a 16-QAM LTE 250 MHz signal at 26 GHz, and the output spectrum at 6.4 dBm $P_{OUT,avg}$ is shown in Fig. 9. The SiGe PA shows excellent linearity at 6.4 dBm $P_{OUT,avg}$, with ACLR1$^-$/ACLR1$^+$ of -38.6/-37.3 dBc, respectively.

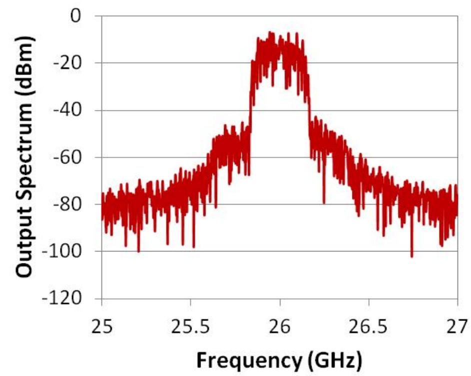


Fig. 9  PEX simulated output spectrum of the broadband SiGe PA with LTE 16QAM modulated 250 MHz signal at 26 GHz, $P_{OUT,\ avg.}$ = 6.4 dBm

## IV. Conclusion

In this work, we have presented a highly efficient broadband SiGe PA design potentially suitable for 5G multi-band operations from 24-32.5 GHz. The PA bandwidth and linearity performance is shown to be robust vs. change in $V_B$ from 0.83-0.85 V and $V_{CC}$ from 1.0-1.4 V and with very high PAE >31.4% across the 8.5 GHz bandwidth. The PA is able to achieve good linearity with 16-QAM LTE modulated 250 MHz signal at $P_{OUT,avg}$ = 6.4 dBm and 26 GHz. To the authors' best knowledge, the extraction-simulated peak PAE of 40.2%/41.2% at 26 GHz with 12.4 dBm is among the very highest peak PAE reports of broadband silicon-based PAs in the 24-32.5 GHz range.

## Acknowledgment

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TABLE II PERFORMANCE SUMMARY OF OUR BROADBAND MM-WAVE SIGE PA VS. THE STATE-OF-THE-ARTS IN THE LITERATURE

| Reference | [8] | [11] | | [13] | This work | |
|---|---|---|---|---|---|---|
| Technology | 28-nm CMOS | 130-nm SiGe BiCMOS | | 28-nm CMOS | 90-nm SiGe BiCMOS[4] | |
| Design | 2-stage, transformer combined | 1-stage, adaptive bias | | 2-stage | 1-stage, CE | |
| Freq (GHz) | 30 | 6-37.7[2] | 20-30 | 30 | 26 | 24-32.5 |
| $P_{OUT,sat}$ (dBm) | 14 | 13.6 | >12 | 14 | 14.2 | >13.3 |
| $P_{1dB}$ (dBm) | 13.2 | N/A | N/A | 13.2 | 10.9 | >10 |
| Peak PAE (%) | 35.3 | 40.9 | >31.1 | 35.5 | 40.2/41.2 ($V_{cc}$=1.2/1.4V) | >31.4 |
| PAE @ $P_{1dB}$ (%) | 34.3 | N/A | N/A | 34.3 | 35.9 | >28.2% |
| Gain $S_{21}$ (dB) | 15.7 | 5.5-8.5 | | 15.7 | 11.5 | >8.5 |
| Chip area ($mm^2$) | 0.385[3] | 0.6 | | 0.163 | 0.57 | |
| Signal Type/PAPR | – | – | – | 64-QAM OFDM/9.6 dB | 16-QAM LTE/7.5 dB | |
| RF BW (MHz) | – | – | – | 250 | 250 | |
| $P_{OUT}$@ACLR= ~-27dBc(dBm) | – | – | – | 4.2 | >6.4 (est. >8) | |
| ACLR1 (dBc) | – | – | – | -28.3/-26.45 @$P_{OUT}$=4.2 dBm | -38.6 /-37.3 @$P_{OUT}$=6.4 dBm | |

[1] Estimated from plots    [2] 3-dB BW    [3] Graphically estimated    [4] Simulation with post-layout parasitic extraction (PEX)