A 22-37 GHz Broadband Compact Linear Mm-Wave Power Amplifier Supporting 64-/256-/512-QAM Modulations for 5G Communications

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***Abstract*—This paper presents a transformer-based broadband compact linear millimeter-wave (mm-Wave) power amplifier (PA) for fifth-generation (5G) communications. A prototype PA is implemented in 90nm SiGe BiCMOS. The PA achieves 17.4dB S_{21} at 29.2 GHz with a 3dB bandwidth (BW_{-3dB}) from 21.8GHz to 37GHz. The PA achieves 20.9/20.3 dBm saturated output power (P_{sat}) and 43.7/39.8% peak power added efficiency (PAE_{max}) at 24/28GHz. The P_{1dB} and PAE at P_{1dB} (PAE_{P1dB}) are 20.6/19.4dBm and 41.0/38.1% at 24/28GHz. The PA demonstrates 0.6Gb/s 64-QAM signals at -25.1/-25.0dB rms error vector magnitude (EVM) with 12.6/10.5dBm average P_{out} (P_{avg}) and 17.5/12.6% average PAE (PAE_{avg}) at 24/27GHz, respectively, without digital predistortion (DPD). The PA also demonstrates 0.9Gb/s 512-QAM signals at -30.1dB rms EVM with 8.9dBm P_{avg} and 10.0% PAE_{avg} at 24GHz without DPD.**

***Keywords*—5G, 64-/256-/512-QAM, broadband, linear, millimeter-wave (mm-Wave), peak-to-average power ratio (PAPR), power amplifiers (PAs), saturated output power (P_{sat}), power added efficiency (PAE).**

I. Introduction

The rapid growth of fifth-generation (5G) communication applications have posed stringent performance requirements on future wireless frontends, especially power amplifiers (PAs), including wide and non-contiguous bandwidth, sufficient output power (P_{out}), high linearity, and high energy efficiency. Different bands, e.g., n257 band (26.50–29.50GHz) and n258 band (24.25–27.50GHz) have been specified in the 3GPP 5G New Radio (NR) FR2 [1]. Broadband mm-Wave 5G systems are highly desired for international/cross-network roaming [1]-[16]. In parallel, high-order complex modulation schemes, e.g., 64-/256-QAM will be extensively used in 5G NR to achieve high spectral efficiency and high data rate, which puts stringent requirements on PA linearity and the resulting large peak-to-average power ratio (PAPR) signals make PA energy efficiency critical [2]-[16]. Moreover, phased arrays with a large number of antennas will be extensively leveraged to overcome the path loss, which favours compact silicon-based PAs for low cost and high integrity [1]-[3].

To summarize, broadband compact linear mm-Wave PAs in silicon with high efficiency are highly desired to cover multiple 5G bands. In this paper, we present a transformer-based 21.8-37.0GHz broadband compact linear mm-Wave PA supporting 64-/256-/512-QAM modulations.

This paper is organized as follows. Section II introduces the design of the proposed broadband compact linear mm-Wave PA and a proof-of-concept implementation in a 90nm SiGe BiCMOS process. Comprehensive measurement results are presented in Section III to characterize the prototype PA design, including the small-signal S-parameter results, large signal continuous-wave (CW) results, modulation test results with 64-/256-/512-QAM signals. A comparison with recently reported broadband mm-Wave 5G PAs is also presented.

II. Design of The Broadband Transformer-based mm-Wave PA

The schematic of the proposed broadband compact linear mm-Wave PA is shown in Fig. 1. The PA comprises a transformer-based input balun, a cascode PA stage, and a transformer-based output network. Both the bottom and cascode devices in the PA stage use CBEBC HBT transistors with a size of 2×4×10um. Neutralization capacitors of 86fF are added at the bottom transistors in the cascode PA stage to enhance stability and gain. RC pairs of 32Ω||0.27pF are added at the base of the bottom HBT transistors in the PA stage to further enhance stability.

The PA utilizes a transformer-based output network to achieve low-loss and broad bandwidth. The 3D EM model of the PA output network is shown in Fig. 1. The primary and secondary coils are edge-coupled and both primary and secondary coils use top metal (blue) and second top metal (red) in parallel to improve coupling coefficient and passive efficiency. The output capacitance of the cascode PA stage is absorbed into the output matching network. An additional capacitor is added to achieve broadband operation. 3D EM simulation results of the PA output network are shown in Fig. 2. The PA output network achieves broadband impedance with higher than 79% passive efficiency across 20 to 40 GHz.

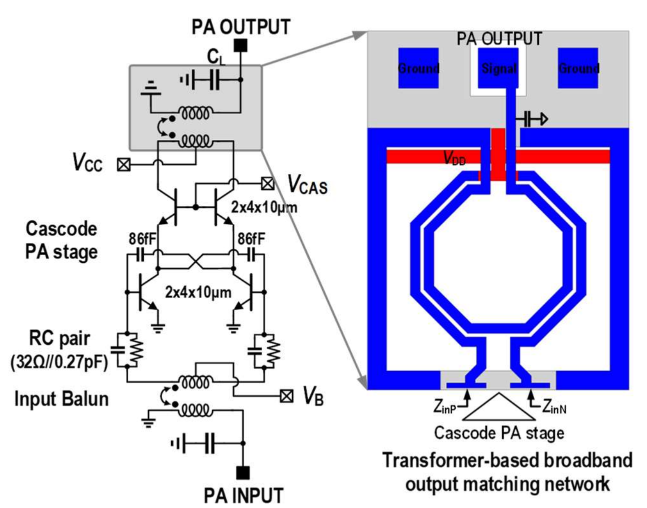
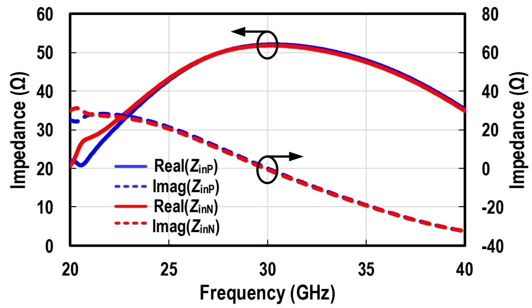
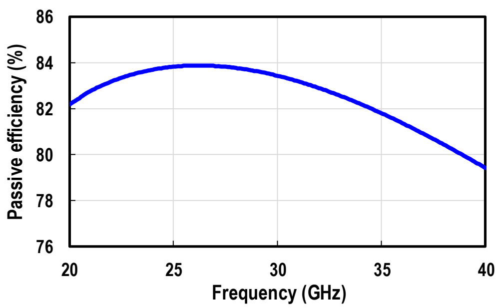


Fig. 1. The PA top schematic and 3D EM model of the transformer-based broadband PA output matching network.



(a)



(b)

Fig. 2. (a) Simulated results of the impedance looking into the transformer-based PA output network (after absorbing the device output capacitance) and (b) the passive efficiency.

III. Experimental Results

A. Prototype Implementation

The proposed transformer-based broadband mm-Wave PA is implemented in 90nm SiGe BiCMOS. The top schematic is shown in Fig. 1. The chip microphotograph is show in Fig. 3. The PA occupies an area of 0.72mm^2 with a core area of only 0.15mm^2.

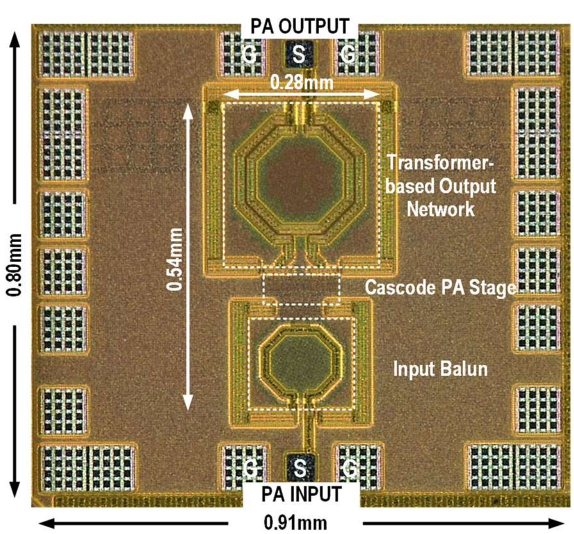


Fig. 3. Chip microphotograph.

B. Small-signal S-parameter Measurement Results

The PA is first characterized for its small-signal S-parameter performance. The measured small-signal S-parameter results are shown in Fig. 4 from 20 to 40 GHz. S_{21} is 17.4 dB at 29.2 GHz with a 3-dB bandwidth BW_{-3dB} from 21.8 to 37.0 GHz. The input matching is better than −10 dB from 23.0 to 36.7 GHz.

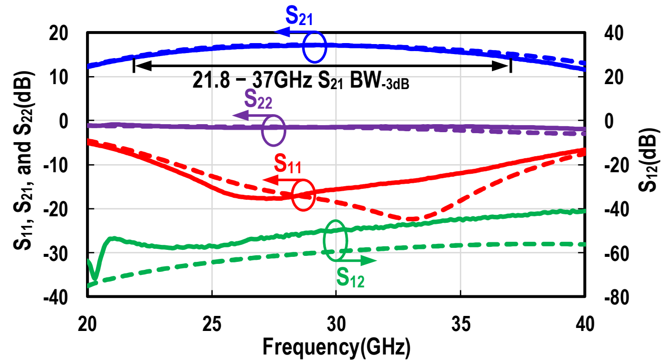
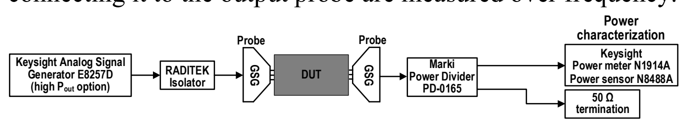


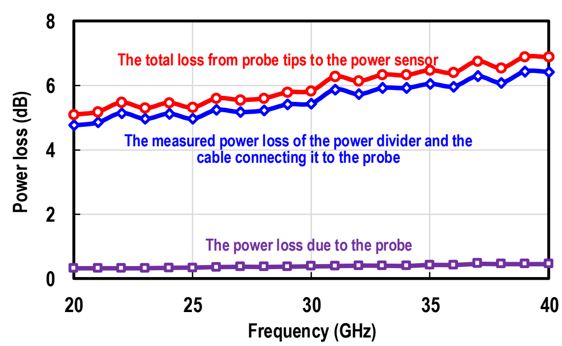
Fig. 4. Small-signal S-parameter measurement results (solid curves) and simulation results (dashed curves).

C. Large-signal Continuous-wave Measurement Results

The PA is further characterized by large-signal continuous-wave (CW) measurements. The setup for large-signal CW measurement is shown in Fig. 5 (a). The input and output power reference planes are at the input/output ground-signal-ground (GSG) probe tips. The power loss from the probe tips to the power sensor is carefully calibrated, as shown in Fig. 5 (b). The power loss of the probes is obtained from the datasheet. The power loss of the Marki Power Divider PD-0165 and the cable connecting it to the output probe are measured over frequency.



(a)



(b)

Fig. 5. (a) Setup for large-signal CW measurement and (b) the power loss calibration.

The large-signal CW results over 20 to 38GHz are shown in Fig. 6. Over 20 to 36GHz, the PA continuously achieves >19.0dBm saturated output power (P_{sat}) with >25% peak PAE (PAE_{max}). The PA performance are shown versus output power (P_{out}) at 24/28GHz. The PA achieves 20.9dBm P_{sat} with 43.7% PAE_{max} and 20.6dBm P_{1dB} with 41.0% PAE at P_{1dB} (PAE_{P1dB}) at 24GHz. The PA also achieves 20.3dBm P_{sat} with 39.8% PAE_{max} and 19.4dBm P_{1dB} with 38.1% PAE at PAE_{P1dB} at 28GHz.

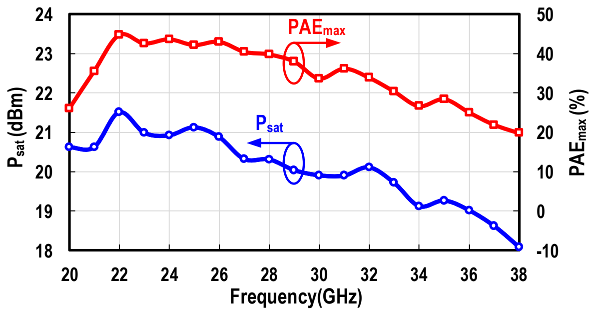
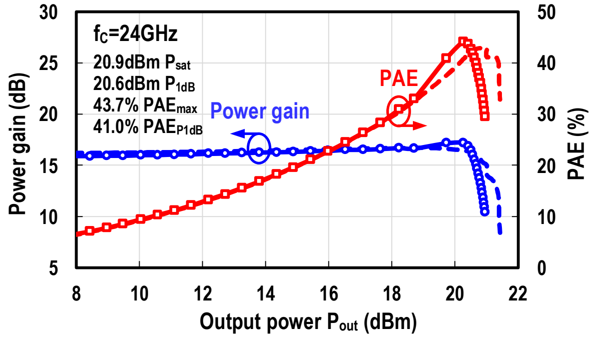
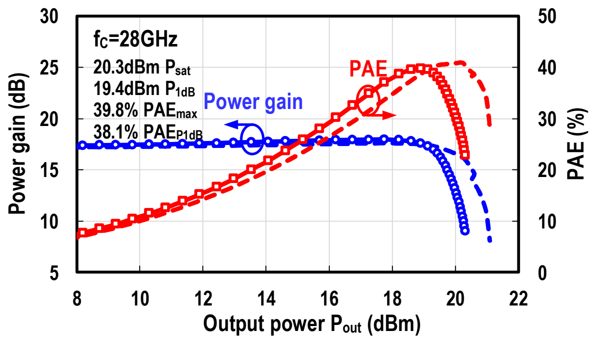


Fig. 6. Measurement results of P_{sat} and PAE_{max} over frequency.



(a)



(b)

Fig. 7. Large-signal CW measurement results (solid curves) and simulation results (dashed curves) (a) at 24GHz (b) at 28GHz.

D. Modulation Test Measurement Results

The PA is further characterized by modulation test. The setup for modulation test measurement is shown in Fig. 8. the input complex-modulated signals are generated by a 4-channel 8-bit Keysight M8195A arbitrary waveform generator (AWG) up-converted by a Marki mixer (MM1-2567LS), filtered, amplified, and then sent to the mm-Wave input of the PA chip. The PA output is demodulated by a Keysight UXA Signal Analyzer (N9040B).

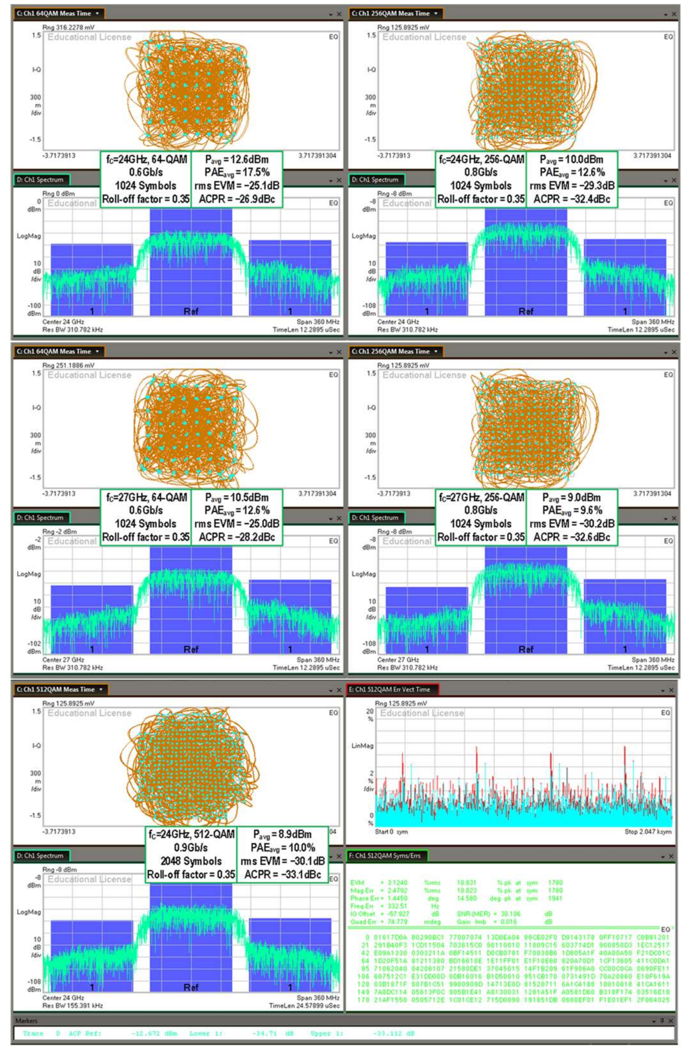


Fig. 9. Modulation test measurement results at 24 and 27GHz.

Figure 9 shows modulation test results using single-carrier signals with no DPD. At 24GHz, the PA achieves -25.1dB rms EVM with 12.6dBm average output power (P_{avg}) and 17.5% average PAE (PAE_{avg}) for 0.6Gb/s 64-QAM signal; the PA achieves -29.3dB rms EVM with 10.0dBm P_{avg} and 12.4% PAE_{avg} for 0.9Gb/s 256-QAM signal. At 27GHz, the PA achieves -25.0dB rms EVM with 10.5dBm P_{avg} and 12.6% PAE_{avg} for 0.6Gb/s 64-QAM signal; the PA achieves -30.2dB rms EVM with 9.0dBm P_{avg} and 9.6% PAE_{avg} for 0.8Gb/s 256-QAM signal. The PA also achieves -30.1dB rms EVM with 8.9dBm P_{avg} and 10.0% PAE_{avg} for 0.9Gb/s 512-QAM signal at 24GHz.

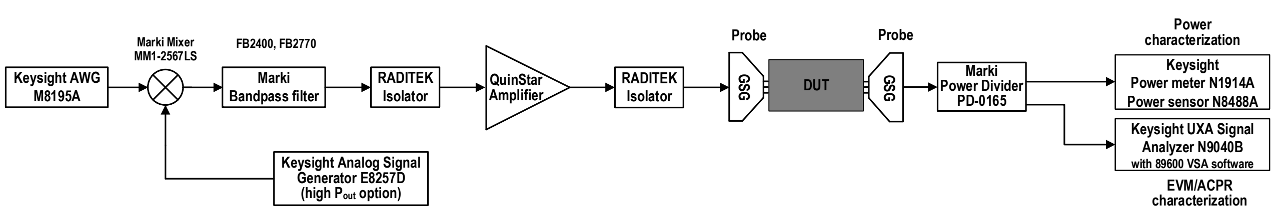


Fig. 8. Setup for modulation test measurement.

Table 1. Comparison with recently reported mm-Wave PAs in silicon.

	This work		Hu, ISSCC 17 [2]	Vigilante, JSSC 18 [3]	Zhang, RFIC 17 [4]	Wang, ISSCC 20 [6]					Chappidi, RFIC 17 [11]	Li, ISSCC 18 [12]	Shakib, ISSCC 17 [5]
Technology	**90nm SiGe BiCMOS**		0.13μm SiGe BiCMOS	28nm CMOS	40nm CMOS	45nm SOI CMOS					0.13μm SiGe BiCMOS	0.13μm SiGe BiCMOS	40nm CMOS
Supply (V)	**3.0**		1.5	0.9	1	2					4.0	1.9	1.1
Gain (dB)	**17.4**		18.2	20.8	20.5	20.5					23.4	20	22.4
S_{21} BW_{-3dB} (GHz)	**21.8-37.0(51%)**		23.3-39.7(52%)	29-57(65%)	26-29(11%)*	25.8-43.4(51%)					N.A.	17.5-31.6(49%)	26-32(21%)*
Freq. (GHz)	**24**	**28**	28	30	27	24	28	37	39	42	40	28.5	27
P_{sat} (dBm)	**20.9**	**20.3**	16.8	16.6	18.1	20	20.4	20	19.1	17.9	23.7	17	15.1
P_{1dB} (dBm)	**20.6**	**19.4**	15.2	13.4	16.8	19.6	19.1	18.9	18.0	15.7	N.A.	15.2	13.7
PAE_{max} (%)	**43.7**	**39.8**	20.3	24.2	41.5	38.9	45.0	38.7	38.6	35.0	28.5	43.5	33.7
PAE_{P1dB}(%)	**41.0**	**38.1**	19.5	12.6	37.6	38.9	42.5	37.7	37.3	30.4	N.A.	39.2	31.1
Modulation scheme	**64-QAM**		64-QAM	64-QAM	64-QAM	5G NR FR2 64-QAM 2-CC OFDM					16-QAM	64-QAM	64-QAM 8-CC OFDM
Freq. (GHz)	**24**	**27**	28	28	27	24	28	37	39	42	50	28.5	27
Data rate (Gb/s)	**0.6**	**0.6**	6	3	1.5	800MHz					4	6	800MHz
EVM (dB)	**-25.1**	**-25.0**	-26.6	-25.0	-25	-25.1	-25.1	-25.1	-25.1	-25.1	-19.2	-27.6	-25
ACPR (dBc)	**-26.9**	**-28.2**	-25.4	-37.6	N.A.	-25.2	-25.6	-27.9	-26.1	-26.4	-30	N.A.	-29.4
P_{avg} (dBm)	**12.6**	**10.5**	7.2	6.8	9.65	10.9	11.3	10.2	10.2	8.4	16.9	10.7	6.7
PAE_{avg}(%)	**17.5**	**12.6**	14.4**	2.9	11.8	14.2	16.6	13.6	13.4	10.3	24.6**	21.4	11
Area (mm^2)	**0.72 (0.15‡)**		1.76	0.16‡	0.36‡†	1.35 (0.21‡)					1.85 (0.96‡)	0.29‡	0.225‡

graphically estimated **last stage collector efficiency ‡core area †with input/output pad

Compared with other recently reported mm-Wave PAs in silicon (Table. 1), the proposed PA achieves state-of-the-art CW performance with a very compact core chip area. It also demonstrates the capability of supporting high-speed 64-/256-QAM signals at 24/27GHz.

IV. Conclusion

This paper presents a transformer-based broadband compact linear mm-Wave PA 5G communications. The prototype PA is implemented in a 90nm SiGe BiCMOS process. The PA achieves state-of-the-art performance compared with recently reported mm-Wave PAs in silicon. It achieves 17.4dB S_{21} at 29.2 GHz with a BW_{-3dB} from 21.8GHz to 37GHz. The PA achieves 20.9/20.3 dBm P_{sat} and 43.7/39.8% PAE_{max} at 24/28 GHz. The P_{1dB} and PAE_{P1dB} are 20.6/19.4 dBm and 41.0/38.1% at 24/28 GHz. The PA demonstrates 64-/256-/512-QAM signals at 24/27 GHz without DPD.

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