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Monolithic Microwave Integrated Circuits (MMIC) Broadband Power Amplifiers (Part 2)

by John E. Penn

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14. ABSTRACT

A broadband amplifier design approach for microwave monolithic integrated circuits (MMICs) was previously documented in a technical report, ARL-TR-6278, *Monolithic Microwave Integrated Circuits (MMIC) Broadband Power Amplifiers*, December 2012. The three amplifier designs previously fabricated and tested as part of the fall 2011 Johns Hopkins University (JHU) MMIC Design Course, taught by the author, covered 2–6, 5–11, and 28 GHz. Since there was extra space available in the fall 2012 JHU MMIC Design Course fabrication, two additional amplifiers were designed, fabricated, and tested following the same design approach. This follow-up technical note documents the two recent amplifier designs, one was designed for 1–5 GHz operation and the second for 10–19 GHz operation.

15. SUBJECT TERMS

MMIC, broadband, power amplifier, GaAs

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1. Introduction

Amplifier design is a tradeoff of gain, bandwidth, noise performance, power performance, efficiency, stability, and impedance match. The following broadband amplifier design approach emphasizes good output power and efficiency, with broadband gain and match. Previously, three amplifier designs were fabricated in TriQuint Semiconductor's 0.13-µm TQP13 gallium arsenide (GaAs) process and tested as part of the fall 2011 Johns Hopkins University (JHU) Monolithic Microwave Integrated Circuit (MMIC) Design Course, taught by the author, covering 2–6, 5–11, and 28 GHz. Since there was extra space available in the fall 2012 JHU MMIC Design Course fabrication, two additional amplifiers using the TQP13 process were designed, fabricated, and tested following the same broadband power amplifier design approach. One amplifier was designed for a lower band of 1–5 GHz operation, while the second was designed for 10–19 GHz operation.

2. Design Approach

The design approach follows the double "Q" output matching described in ARL-TR-6278[1]. After designing the broadband output match for good efficiency and bandwidth, a simple high-pass, low-pass (HP/LP) input match is used to achieve good return loss across the full bandwidth, which is constrained by the transistor's parasitics. Simulations using Microwave Office (MWO) with the TriQuint TQP13 0.13-µm pseudomorphic high electron mobility transistor (PHEMT) process are shown for each of the two amplifier designs.

3. A 1–5 GHz Broadband Power Amplifier

The broadband design approach was used for an amplifier centered at 2 GHz. Figure 1 shows the layout of the 1–5 GHz amplifier. A simple low-pass input match consisting of a shunt capacitor and series inductor provided a compromise with fair input return loss and broadband gain. This design used a 6 x 65 µm PHEMT, instead of the standard 6 x 50 µm PHEMT used in the other broadband designs. A compromise was struck between the best output power and best efficiency using the nonlinear model for load-pull equivalent simulations (figures 2 and 3). Best output match was chosen as 65 Ω in parallel with 184 fF, for a "Q" of 0.2. Using the two load contour simulations, this output match should yield 20.8 dBm of output power at 61% power-added

[1]Penn, J. *Monolithic Microwave Integrated Circuits (MMIC) Broadband Power Amplifiers*; ARL-TR-6278; U.S. Army Research Laboratory: Adelphi, MD, December 2012.

efficiency (PAE) (2 GHz). This estimate uses the TQP13 TOM4 nonlinear model biased at 4 V DC with ideal lossless matching elements.

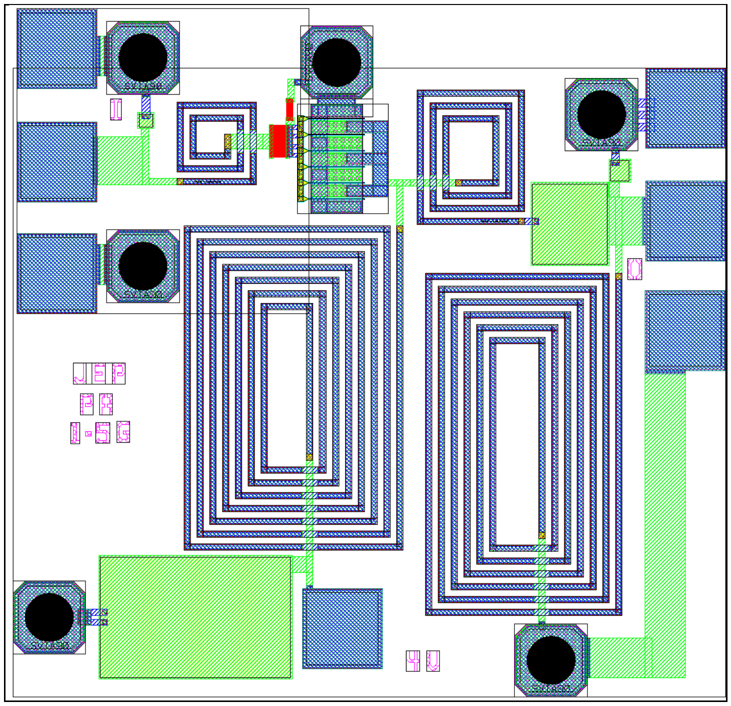

Figure 1. Layout plot of the 1–5 GHz power amplifier (~0.9 x 0.9 mm).

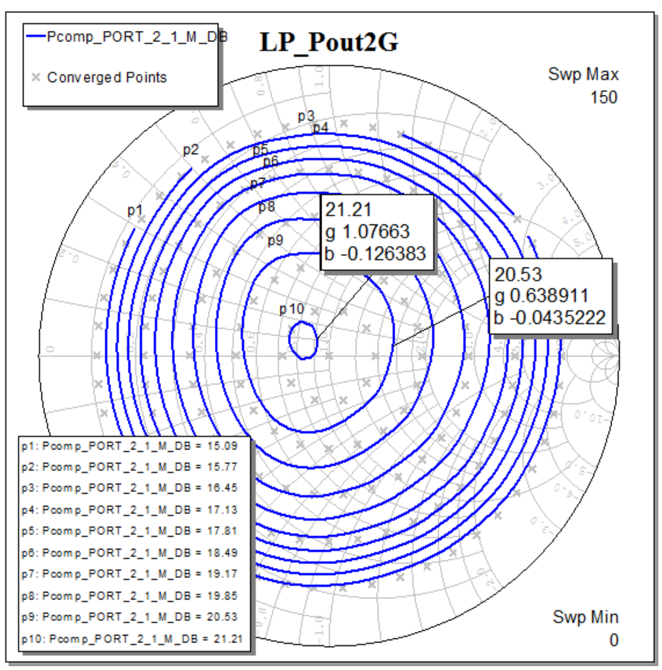

Figure 2. A 2-GHz load-pull simulation of output power (Pcomp-6 x 65 µm PHEMT).

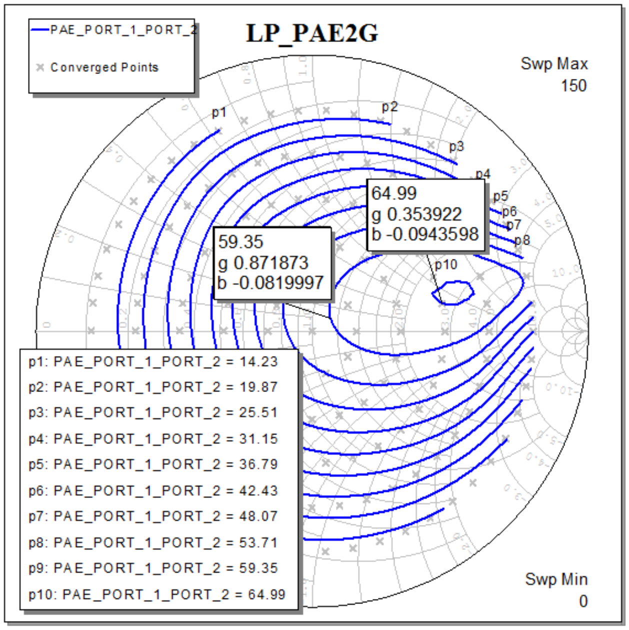

Figure 3. A 2-GHz load-pull simulation of PAE (6 x 65 µm PHEMT).

After designing the stabilizing network, input matching network, and output matching network using TriQuint library elements, the final layout is simulated with MWO to predict the S-parameter performance. Additional Sonnet EM simulations of the actual layouts were also performed, which were similar to the linear MWO simulations with a slight "typical" down-shift in frequency performance. Figure 4 shows the actual measured results (solid) versus the linear MWO simulations (dot-dash) and the Sonnet EM simulations (dotted). For this example, the measurements appear to be in closer agreement to the original MWO linear simulations. Both simulations agree well with the measurements.

A nonlinear simulation of the 1–5 GHz MMIC for expected output power and PAE at 1, 2, 3, and 4 GHz predicts better than 20.9 dBm of output power (120 mW) and greater than 46% PAE, with a peak of 54% PAE at 2 GHz (figure 5). Gain falls off with increasing frequency for GaAs PHEMTs, so for each of these broadband designs, the higher gains are at the lower end of the operating band.

Actual measured performance at 1, 2, 3, 4, and 5 GHz is shown in table 1. The output power (Pout(corr)) and PAE were lower than predicted, but consistent with the previous designs. Best output power was about 19 dBm and 35% PAE at 3 and 4 GHz (4 V DC bias).

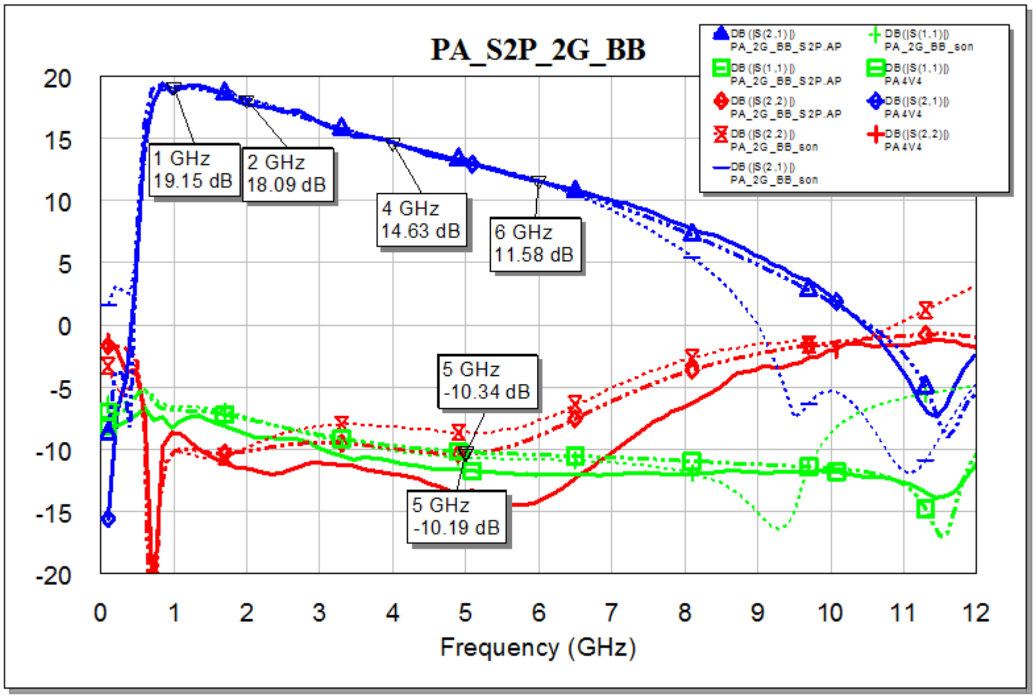

Figure 4. MMIC 1–5 GHz broadband power amplifier linear simulations versus measured (solid).

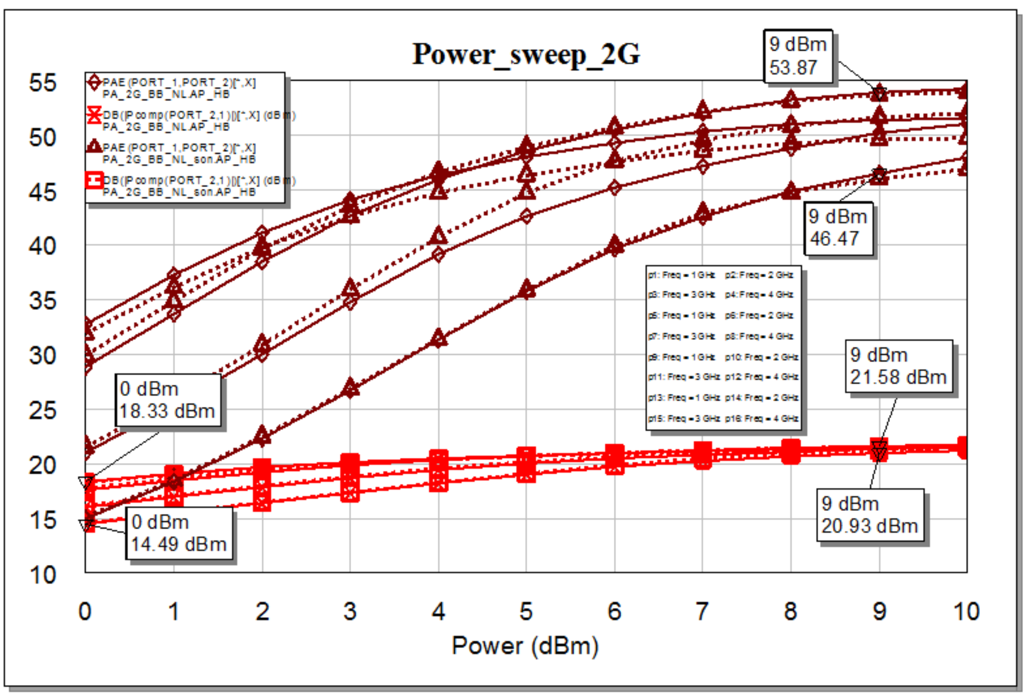

Figure 5. MMIC 1–5 GHz output power and PAE performance simulation (1, 2, 3, and 4 GHz).

Table 1. Power performance for the 1–5 GHz broadband amplifier.

1 GHz	Die#1	**1-5 GHz Fall12 TQP13**				4V ; 53 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-10.0	7.78	-10.60	8.38	18.98	53	212.0	6.89	3.2	3.2
-5.0	12.77	-5.60	13.37	18.97	53	212.0	21.73	10.2	10.1
-2.0	15.36	-2.60	15.96	18.56	53	212.0	39.45	18.6	18.3
0.0	16.70	-0.60	17.30	17.90	53	212.0	53.70	25.3	24.9
2.0	17.45	1.40	18.05	16.65	53	212.0	63.83	30.1	29.5
4.0	17.76	3.40	**18.36**	14.96	53	212.0	68.55	32.3	**31.3**

2 GHz	Die#1	**1-5 GHz Fall12 TQP13**				4V ; 53 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-10.0	6.13	-10.90	7.03	17.93	53	212.0	5.05	2.4	2.3
-5.0	11.19	-5.90	12.09	17.99	53	212.0	16.18	7.6	7.5
-2.0	14.09	-2.90	14.99	17.89	53	212.0	31.55	14.9	14.6
0.0	15.75	-0.90	16.65	17.55	53	212.0	46.24	21.8	21.4
2.0	16.91	1.10	17.81	16.71	53	212.0	60.39	28.5	27.9
4.0	17.41	3.10	**18.31**	15.21	53	212.0	67.76	32.0	**31.0**

3 GHz	Die#1	**1-5 GHz Fall12 TQP13**				4V ; 53 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-2.0	12.41	-3.05	13.46	16.51	53	212.0	22.18	10.5	10.2
0.0	14.33	-1.05	15.38	16.43	53	212.0	34.51	16.3	15.9
2.0	16.02	0.95	17.07	16.12	53	212.0	50.93	24.0	23.4
4.0	17.21	2.95	18.26	15.31	53	212.0	66.99	31.6	30.7
5.0	17.56	3.95	18.61	14.66	53	212.0	72.61	34.3	33.1
6.0	17.80	4.95	**18.85**	13.90	53	212.0	76.74	36.2	**34.7**

4 GHz	Die#1	**1-5 GHz Fall12 TQP13**				4V ; 53 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
0.0	11.59	-1.35	12.94	14.29	53	212.0	19.68	9.3	8.9
2.0	14.14	0.65	15.49	14.84	53	212.0	35.40	16.7	16.2
4.0	15.88	2.65	17.23	14.58	53	212.0	52.84	24.9	24.1
5.0	16.57	3.65	17.92	14.27	53	212.0	61.94	29.2	28.1
6.0	17.15	4.65	18.50	13.85	53	212.0	70.79	33.4	32.0
7.0	17.62	5.65	**18.97**	**13.32**	53	212.0	78.89	37.2	**35.5**

5 GHz	Die#1	**1-5 GHz Fall12 TQP13**				4V ; 53 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
0.0	10.16	-1.60	11.76	13.36	53	212.0	15.00	7.1	6.7
2.0	12.46	0.40	14.06	13.66	53	212.0	25.47	12.0	11.5
4.0	14.22	2.40	15.82	13.42	53	212.0	38.19	18.0	17.2
6.0	15.56	4.40	17.16	12.76	53	212.0	52.00	24.5	23.2
7.0	16.13	5.40	17.73	**12.33**	53	212.0	59.29	28.0	**26.3**
8.0	16.62	6.40	**18.22**	**11.82**	53	212.0	66.37	31.3	**29.2**

4. A 10–19 GHz Broadband Power Amplifier

The broadband design approach was used for an amplifier centered at 16 GHz. Figure 6 shows the layout of the 10–19 GHz amplifier. A simple HP/LP input match provided good input return loss and broadband gain. This design used the nominal 6 x 50 μm PHEMT. A compromise was struck between the best output power and best efficiency using the nonlinear load-pull contour simulations (figures 7 and 8). Best output match was chosen as 70 Ω in parallel with 165 fF, for a "Q" of 1.2. Using the two performance load contours, this output match should yield 20.0 dBm of output power at 45% PAE (16 GHz). This estimate uses the TQP13 TOM4 nonlinear model biased at 4 V DC with ideal lossless matching elements.

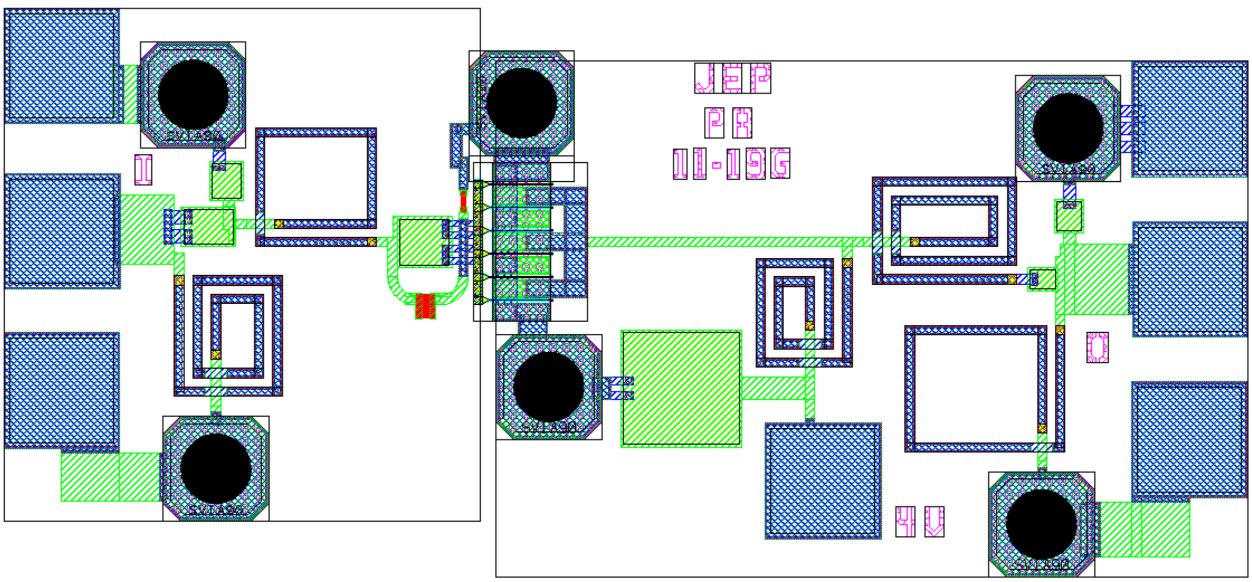

Figure 6. Layout plot of the 10–19 GHz power amplifier (~1.1 x 0.5 mm).

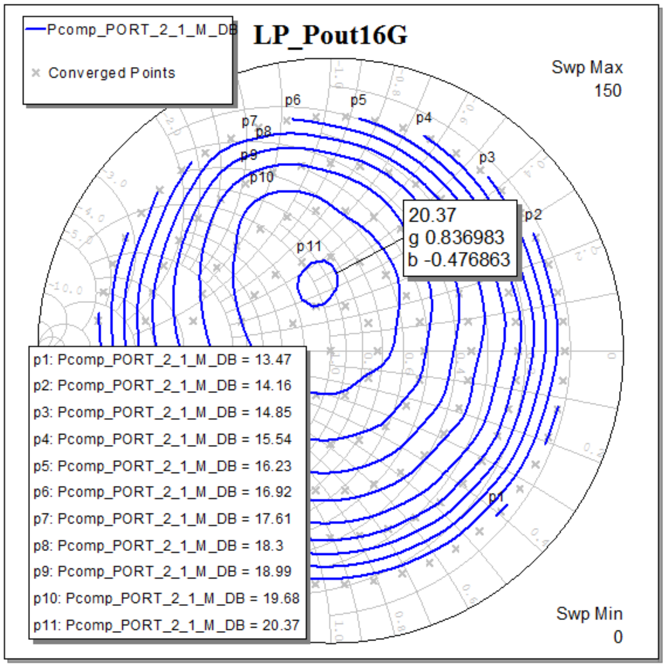

Figure 7. A 16-GHz load-pull simulation of output power (Pcomp-6 x 50 µm PHEMT).

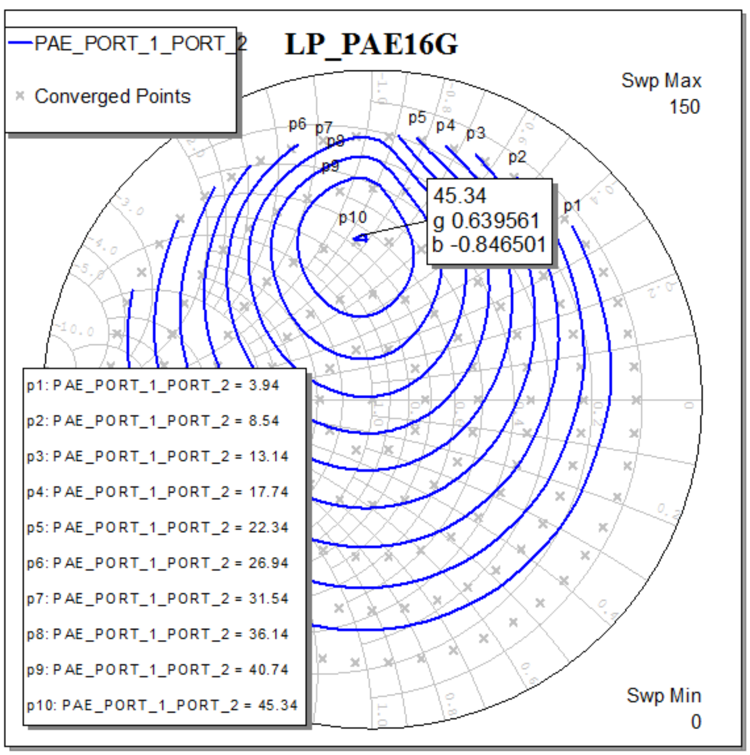

Figure 8. A 16-GHz load-pull simulation of PAE (6 x 50 µm PHEMT).

After designing the stabilizing network, input matching network, and output matching network using TriQuint library elements, the final layout is simulated with MWO to predict the S-parameter performance. Additional Sonnet EM simulations of the actual layouts were also performed, which were similar to the linear MWO simulations with a slight “typical” down-shift in frequency performance. Figure 9 shows the actual measured results (solid) versus the linear MWO simulations (dot-dash) and the Sonnet EM simulations (dotted). For this example, the measurements appear to be in closer agreement to the MWO linear simulations. Both simulations agree well with the measured performance.

A nonlinear simulation of the 10–19 GHz MMIC for expected output power and PAE at 14, 16, and 18 GHz (figure 10) predicts better than 20.9 dBm of output power (120 mW) and 32% to 39% PAE. Gain falls off with increasing frequency for GaAs PHEMTs, so with each of these broadband designs, the higher gains are at the lower frequency of the operating band.

Actual measured performance at 12, 14, and 16 GHz is shown in table 2. The output power (Pout(corr)) and PAE were lower than predicted, however the amplifier was not driven to its peak performance during testing. Best output power was about 18.4 dBm and 33% PAE at 14 GHz and 1.5 dB compression (4 V DC Bias).

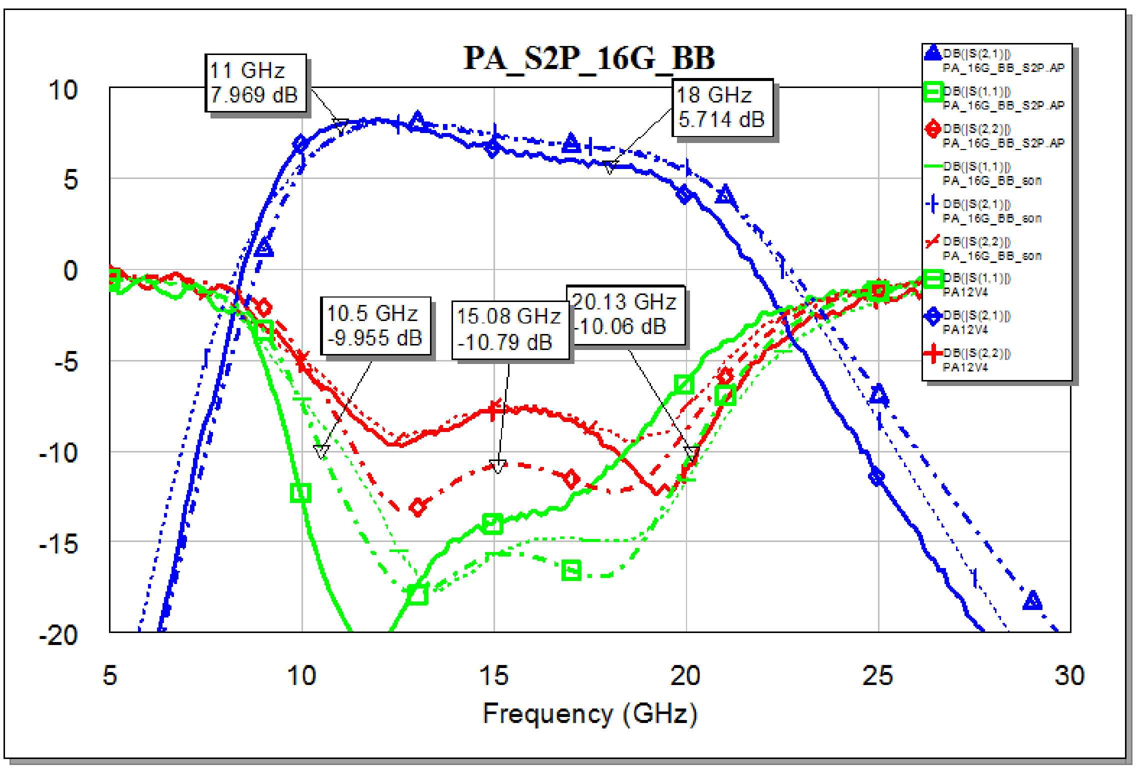

Figure 9. MMIC 10–19 GHz broadband power amplifier linear simulations vs. measured (solid).

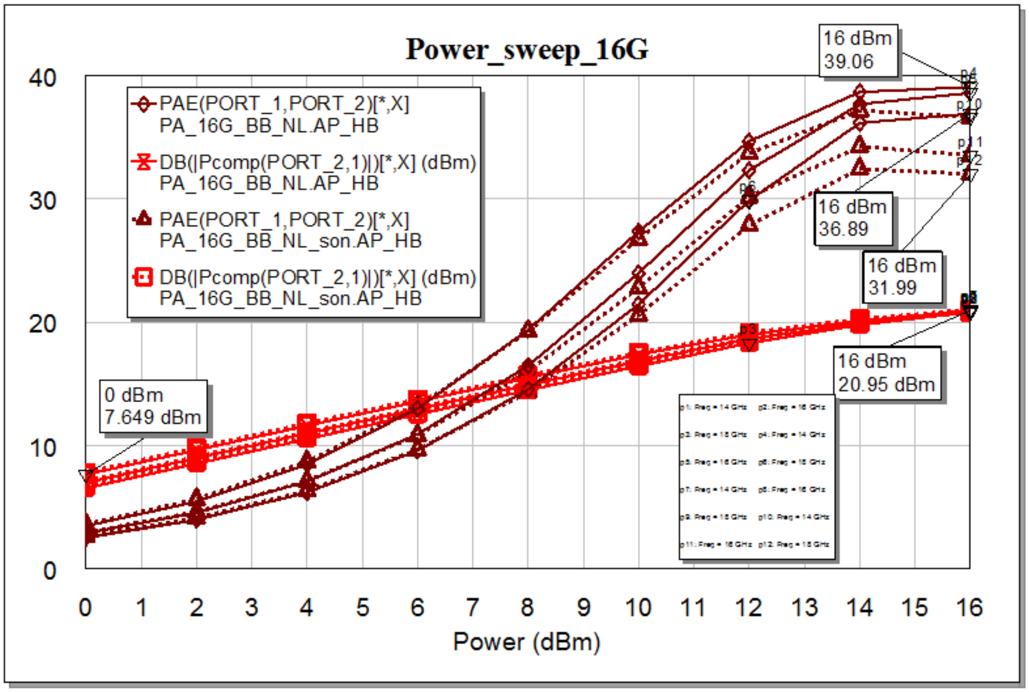

Figure 10. MMIC 10–19 GHz output power and PAE performance simulation (14, 16, and 18 GHz).

Table 2. Power performance for the 10–19 GHz broadband amplifier.

12 GHz	Die#1	11-19 GHz Fall12 TQP13				4V ; 45 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-5.0	-1.32	-7.40	1.08	8.48	45	180.0	1.28	0.7	0.6
0.0	3.67	-2.40	6.07	8.47	45	180.0	4.05	2.2	1.9
5.0	8.71	2.60	11.11	8.51	45	180.0	12.91	7.2	6.2
10.0	13.35	7.60	15.75	8.15	45	180.0	37.58	20.9	17.7
12.0	14.66	9.60	17.06	7.46	47	188.0	50.82	27.0	22.2
14.0	15.43	11.60	**17.83**	6.23	42	168.0	60.67	36.1	**27.5**

14 GHz	Die#1	11-19 GHz Fall12 TQP13				4V ; 45 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-5.0	-1.89	-7.75	0.86	8.61	45	180.0	1.22	0.7	0.6
0.0	3.09	-2.75	5.84	8.59	45	180.0	3.84	2.1	1.8
5.0	8.15	2.25	10.90	8.65	45	180.0	12.30	6.8	5.9
10.0	13.00	7.25	15.75	8.50	45	180.0	37.58	20.9	17.9
12.0	14.58	9.25	17.33	8.08	47	188.0	54.08	28.8	24.3
14.0	15.61	11.25	**18.36**	7.11	42	168.0	68.55	40.8	**32.9**

16 GHz	Die#1	11-19 GHz Fall12 TQP13				4V ; 45 mA			
Pin(SG)	**Pout(SA)**	**Pin(corr)**	**Pout(corr)**	**Gain**	**I1(4V)**	**PDC(mw)**	**Pout(mw)**	**Drn Eff**	**PAE**
-5.0	-3.23	-7.90	-0.33	7.57	45	180.0	0.93	0.5	0.4
0.0	1.73	-2.90	4.63	7.53	45	180.0	2.90	1.6	1.3
5.0	6.77	2.10	9.67	7.57	45	180.0	9.27	5.1	4.2
10.0	11.76	7.10	14.66	7.56	45	180.0	29.24	16.2	13.4
12.0	13.56	9.10	16.46	7.36	47	188.0	44.26	23.5	19.2
14.0	14.92	11.10	**17.82**	6.72	42	168.0	60.53	36.0	**28.4**

5. Conclusion

These broadband medium power amplifier MMICs were designed using some of the techniques taught by Dale Dawson in the JHU Power MMIC Course. Previously, 2–6 and 5–11 GHz broadband amplifiers were documented in technical report, ARL-TR-6278 (December 2012). These two additional designs documented here extend lower (1–5 GHz) and higher (10–19 GHz) in frequency. These broadband filter and matching techniques could be applied to parallel combinations of transistors to increase power, but these simple one-transistor, single-stage designs represent a proof of the design approach using actual fabricated and measured MMICs. It should be noted that these broadband techniques were also used to successfully design two high power broadband MMIC amplifiers at 3–5 and 4–6 GHz using TriQuint's 0.25-µm gallium nitride (GaN) process (see ARL-TR-5987[2] and ARL-TR-6090[3]). Other broadband amplifier designs of increasing difficulty are currently being designed at ARL, extending to higher frequencies, parallel combined output devices, and cascaded gain stages.

These simple one stage MMIC amplifiers illustrate a broadband design approach and the limitations that start with the device parasitics, the quality of the nonlinear and linear models available, and the quality of the MMIC fabrication process.

While these designs were part of a JHU course, the design techniques and Microwave MMICs would be of interest to Army and Department of Defense communications systems, sensors, and wireless systems.

[2]Penn, J. *Broadband, Efficient, Linear C-Band Power Amplifiers designed in a 0.25-µm Gallium Nitride (GaN) Foundry Process from TriQuint Semiconductor*; ARL-TR-5987; U.S. Army Research Laboratory: Adelphi, MD, May 2012.

[3]Penn, J. *Testing of Broadband, Efficient, Linear C-Band Power Amplifiers*; ARL-TR-6090; U.S. Army Research Laboratory: Adelphi, MD, August 2012.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
AWR	Applied Wave Research
GaAs	gallium arsenide
GaN	gallium nitride
HP	high-pass
JHU	Johns Hopkins University
LP	low-pass
MMIC	monolithic microwave integrated circuit
MWO	Microwave Office
PAE	power-added efficiency
PHEMT	pseudomorphic high electron mobility transistor

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