ARL-TR-9146 ● FEB 2021

DEVCOM ARMY RESEARCH LABORATORY

Gallium Nitride (GaN) RF Challenge: DOD Design Team Effort for Qorvo Fabrication

by John E Penn

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John E Penn
Sensors and Electron Devices Directorate, DEVCOM Army Research Laboratory

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
February 2021	Technical Report	1 August–31 October 2020

4. TITLE AND SUBTITLE
Gallium Nitride (GaN) RF Challenge: DOD Design Team Effort for Qorvo Fabrication

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John E Penn

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
DEVCOM Army Research Laboratory
ATTN: FCDD-RLS-ER
Adelphi, MD 20783-1138

8. PERFORMING ORGaNIZATION REPORT NUMBER
ARL-TR-9146

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
ORCID ID: John Penn, 0000-0001-7535-0388

14. ABSTRACT
The Department of Defense (DOD) Gallium Nitride (GaN) RF Challenge is enabling development and fabrication of the best concepts for high-performance, efficient, broadband monolithic microwave integrated circuits related to the 5G expansion and to critical electronic warfare needs. The circuits documented in this report are US Army Combat Capabilities Development Command Army Research Laboratory designs as part of the DOD Design Team for the Qorvo 0.15-µm GaN multiproject wafer fabrication. When these fabricated designs are returned in 2021, they will be tested, evaluated, and documented in future technical reports.

15. SUBJECT TERMS
radio frequency, RF, microwave, monolithic microwave integrated circuit, MMIC, amplifier, gallium nitride, GaN

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			John E Penn
Unclassified	Unclassified	Unclassified	UU	36	19b. TELEPHONE NUMBER (Include area code) (301) 394-0423

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

I acknowledge and thank the US Army Combat Capabilities Development Command Army Research Laboratory team. These designs were a joint effort of Dr Ali Darwish, Sami Hawasli, Ken McKnight, and Khamsouk Kingkeo, who will be heavily involved in testing the designs when they come back from fabrication. Thanks to the RF Gallium Nitride (GaN) Challenge Team and coordinators, especially to Dave Via of the US Air Force Research Laboratory and Anita Pacheco of Qorvo, who helped us get the designs submitted, and helped with many technical questions.

1. Introduction

With the emergence of 5G wireless networks, US Department of Defense (DOD) systems will have to operate in a crowded and contested environment. The DOD Gallium Nitride (GaN) RF Challenge is enabling development and fabrication of the best competed concepts for high-performance, efficient, broadband monolithic microwave integrated circuits (MMICs) related to the 5G expansion and to critical electronic warfare needs. Two different GaN foundries, BAE and Qorvo, will fabricate the many competed circuit ideas as part of this effort. The circuits documented in the following are part of the DOD design team's fabrication space on the Qorvo 0.15-µm GaN multiproject wafer fabrication. The US Army Combat Capabilities Development Command Army Research Laboratory was also part of the DOD design team for the BAE 0.18-µm GaN multiproject wafer fabrication, and those designs are documented in other technical reports.

2. Redo Dual S-/X-Band 5-W Power Amplifier (PA) Design

A number of circuits were designed, fabricated, and tested as part of a multiproject Qorvo 0.15-µm GaN prototype wafer-fabrication effort.[1] One of those circuits, a dual-band S-/X-band PA design, suffered from an odd-mode stability issue. Odd-mode resistors were added using a focused-ion-beam process to a couple of die to stabilize the designs for testing. With the availability of die space on the GaN RF Challenge for DOD designers using the Qorvo 0.15-µm GaN process, this was a good chance to correct and improve this critical PA design by adding the necessary odd-mode resistors. If the odd-mode could be stabilized, the dual-band PA should operate as originally intended.

The original PA layout by Ken McKnight used a 4- × 2-mm die size, so it needed to be convoluted into a new 2.15- to 3-mm die space without changing the original performance while adding the correction to the odd-mode stability. Figure 1 shows the original layout in the 4- × 2-mm die size, while Fig. 2 shows the updated layout in a 2.15- to 3-mm die size, which should only differ in the addition of odd-mode resistors on the gate and an update of the values of the existing odd-mode resistors on the drain. First, the gate and drain feed layouts to the combined high-electron-mobility transistors (HEMTs) were Axiem electromagnetic (EM)-simulated for use in evaluating the odd-mode stability. The Microwave Office (MWO) schematic of the odd-mode instability simulation is shown in Fig. 3, with the potential oscillation below 9 GHz shown in Fig. 4. In the original PA design, odd-mode resistors were added between the drains of the two HEMTs, but were insufficient in the actual PA to prevent an odd-mode oscillation near 9 GHz. A re-analysis was performed,

calculating the resistor value needed on the drain to make the real part greater than zero (e.g., non-negative). Additionally, an odd-mode resistor value on the gate was calculated for achieving odd-mode stability. Then, *both* gate and drain odd-mode resistors were added to the two HEMTs, creating a large positive stability margin, as shown in Fig. 5. The even mode, or normal, operation of the redesigned S-/X-band PA should now be as originally intended. Performance of the PA will be verified when the fabricated circuit is returned from Qorvo sometime in 2021.

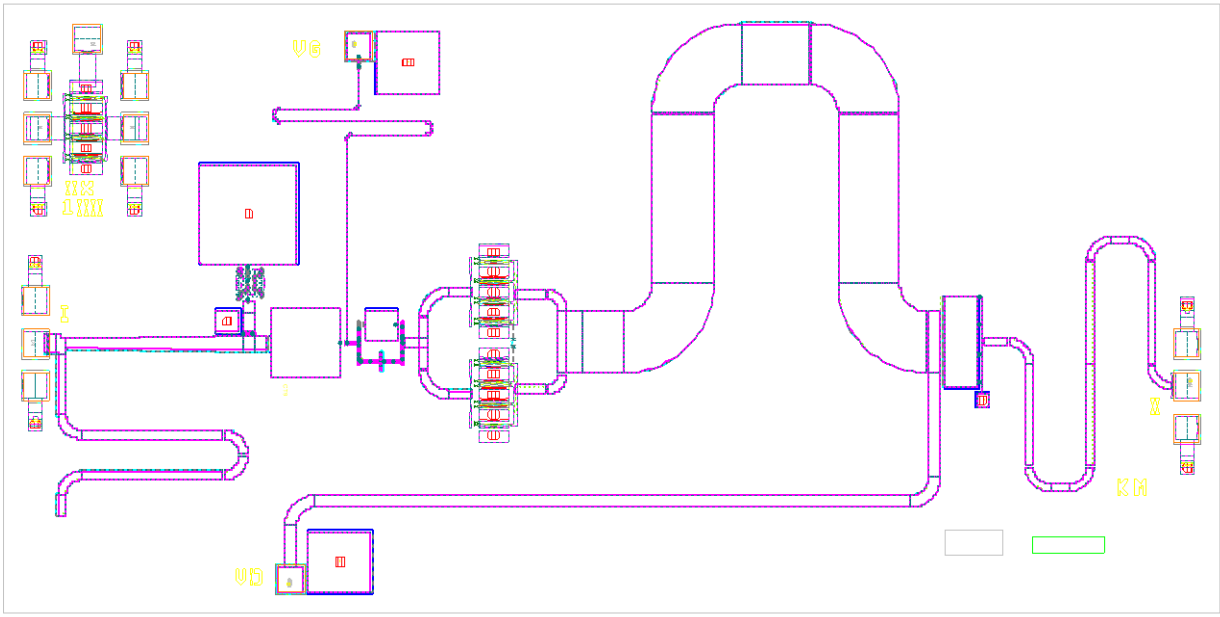

Fig. 1 McKnight original dual S-/X-band ~5-W PA Qorvo 0.15-µm GaN (4.0 × 2.0 mm)

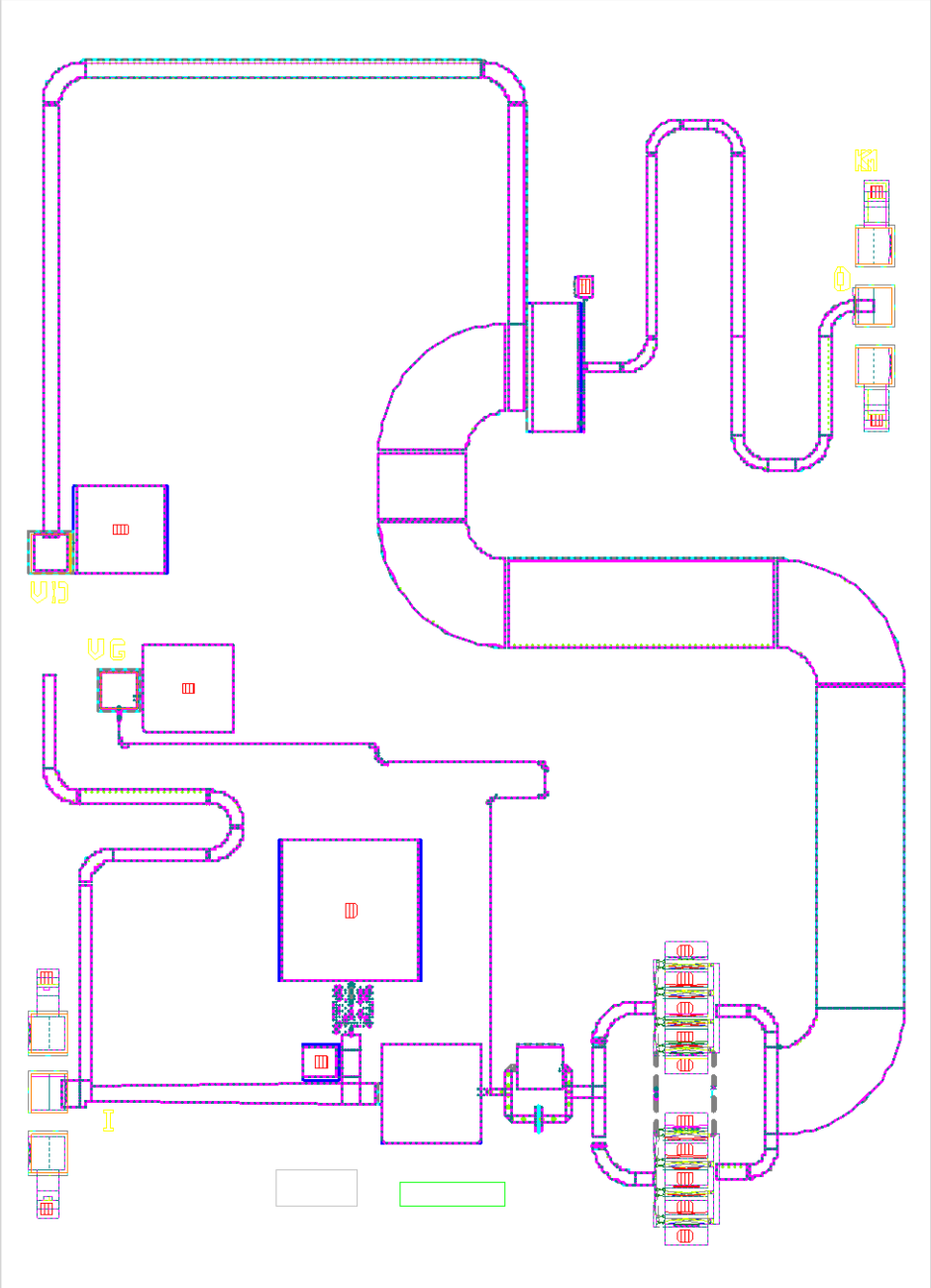

Fig. 2 McKnight dual S-/X-band ~5-W PA with odd-mode fix Qorvo 0.15-µm GaN (2.15 × 3.0 mm)

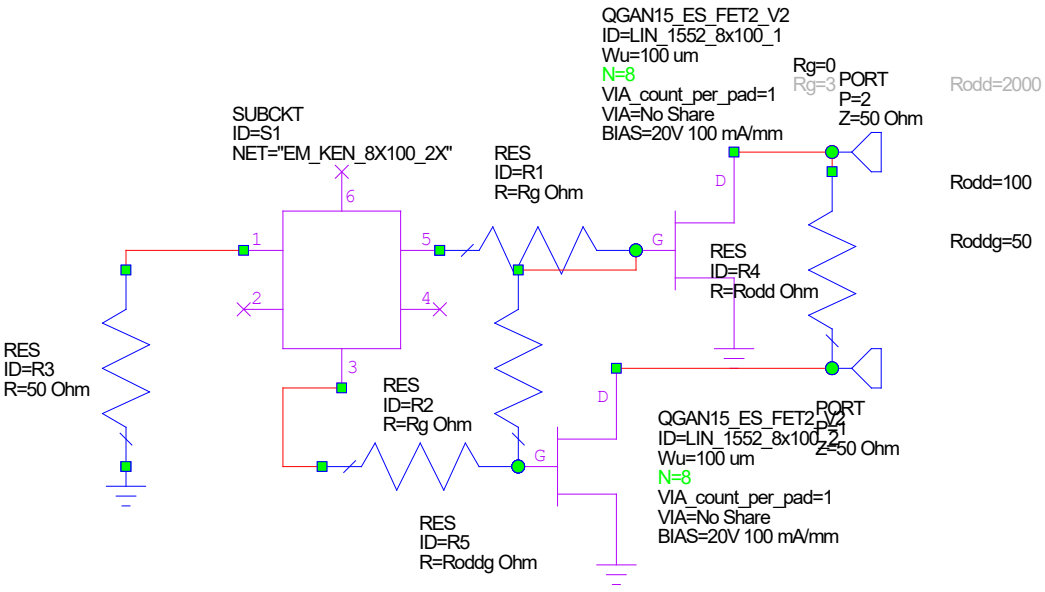

Fig. 3 Simple schematic to evaluate odd-mode stability of combiner portion of PA

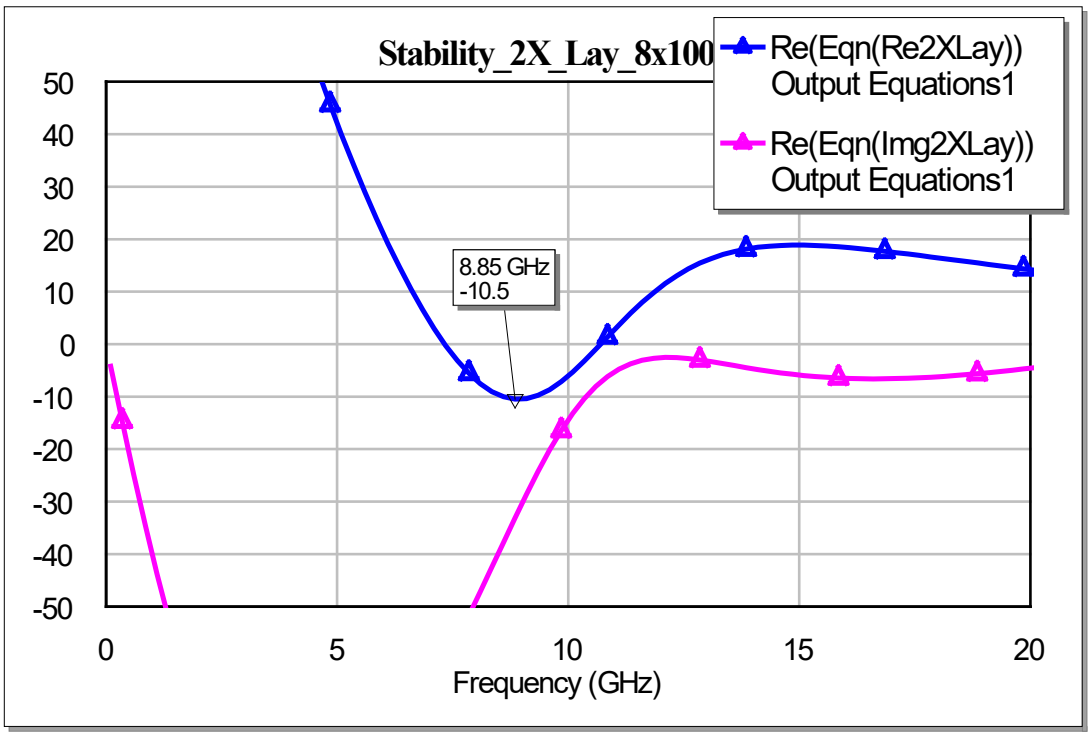

Fig. 4 Odd-mode stability analysis without odd-mode resistors for PA

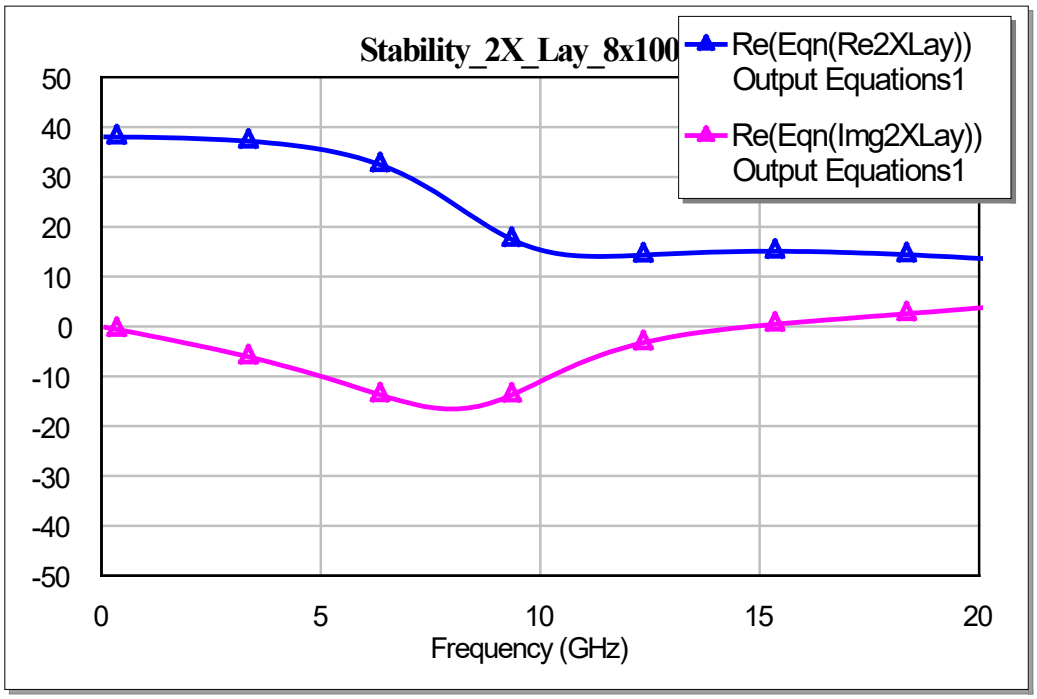

Fig. 5 Odd-mode stability analysis with both gate and drain odd-mode resistors for PA

The full original layout and new modified layout were EM-simulated to make sure the convolutions and contortions in modifying the PA layout did not break anything or change the original performance. It may be hard to see in the plot (Fig. 6), but there is a faint trace that is nearly identical in shape to the solid traces, showing that the two layouts are essentially equivalent.

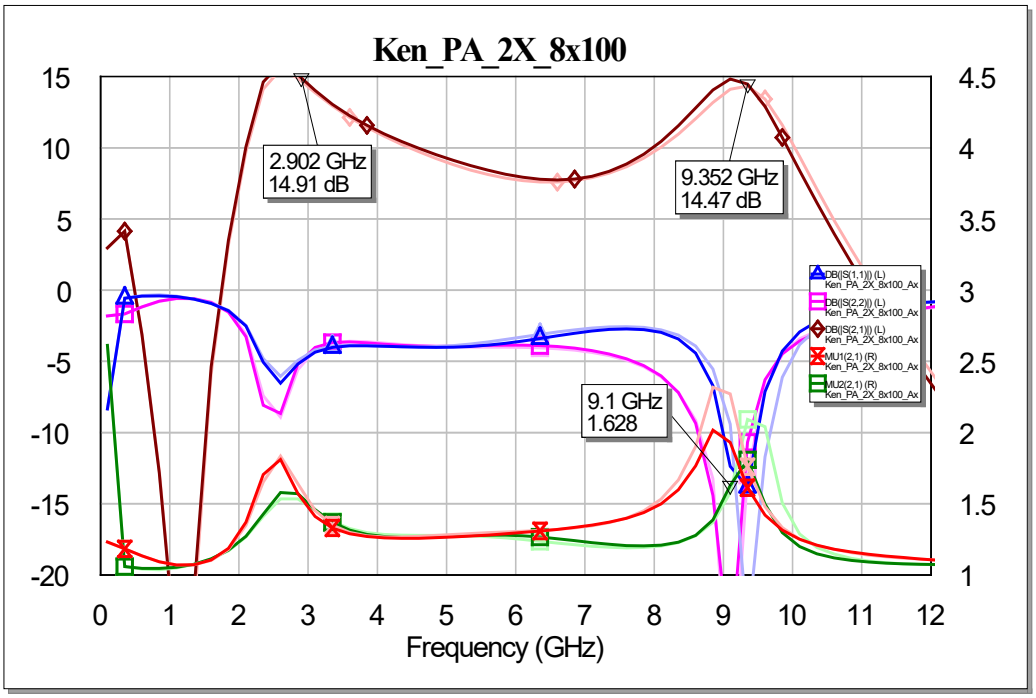

Fig. 6 S-parameter simulation of old and new S-/X-band ~5-W PA (Axiem EM)

3. Broadband S-/X-Band 10-W PA Design

A recent broadband S- to X-band PA was designed and successfully tested.[2] Given the opportunity to improve the design, the PA was redone with the addition of a driver amplifier stage for higher gain. Due to the addition of a broadband driver amplifier to the PA, the input match of the output stage had to be compacted slightly by meandering the input lines to make room for the driver stage. The original broadband 10-W PA was on a 2-mm-wide die; the new die size was 2.15–3 mm. Between the input match layout shrink and the extra 0.15-mm die width, the added driver stage was squeezed into a redesigned two-stage 10-W PA. Also, two identical mirror images of the PA fit within the height of the new die size (Fig. 7). This mirror image allows for the two 10-W amplifiers to be combined into a 20-W design in a higher-level assembly.

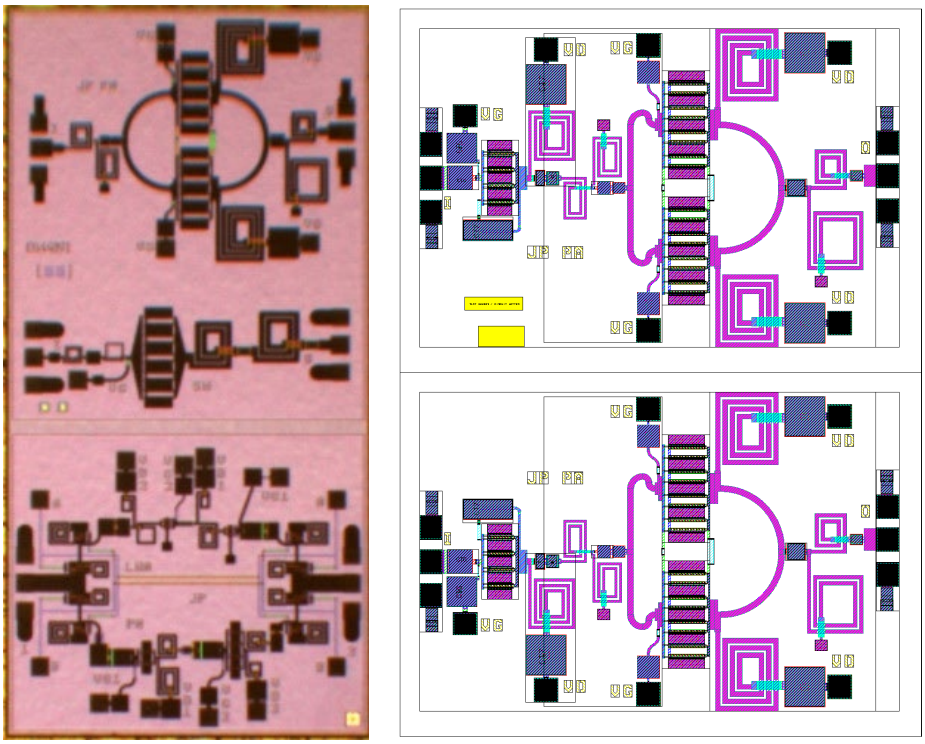

Fig. 7 (Left) original CKT9 with broadband S- to X-band 10-W PA (top left: 2- × 4-mm die) and (right) final duplicate two-stage 10-W PAs in 2.15- × 3-mm die plot

Since the design time available before tapeout was short, a simple feedback amplifier was developed for the first-stage driver. A feedback amplifier should be broadband but would likely have a decreasing gain with frequency. To offset this negative gain slope, a simple two-element low-pass filter (LPF) was added to flatten the gain slope and provide the DC drain voltage through the shunt inductor of the LPF. The power output of the driver stage needed to be sufficient to ensure that it would not compress before the output stage of the PA compressed. The small signal gain of a 6- × 100-µm broadband feedback amplifier design was similar to an 8- × 100-µm broadband feedback amplifier design, as shown in Fig. 8. Since both had similar small signal gain, the nonlinear performance was simulated next to verify that these designs generated sufficient power to drive the 10-W output stage. The schematics of the 6- × 100-µm feedback amplifier and its associated power performance with a 20-V DC drain bias are shown in Figs. 9 and 10, while the schematics of the 8- × 100-µm feedback amplifier and its associated power performance with a 20-V DC drain bias are shown in Figs. 11 and 12. Since output power and efficiency are higher in the 8- × 100-µm driver stage, the 8- × 100-µm design was chosen for the driver stage. A simple shunt-inductor-series capacitor LPF was inserted between the driver amp and the two-way combiner 10-W output stage. Figure 13 shows the relatively flat gain of the original one-stage PA versus the two-stage PA, which increases the small-signal gain to be about

20 dB, or more, from S- to X-band. A plot of the final layout of the two-stage PA is shown in Fig. 14.

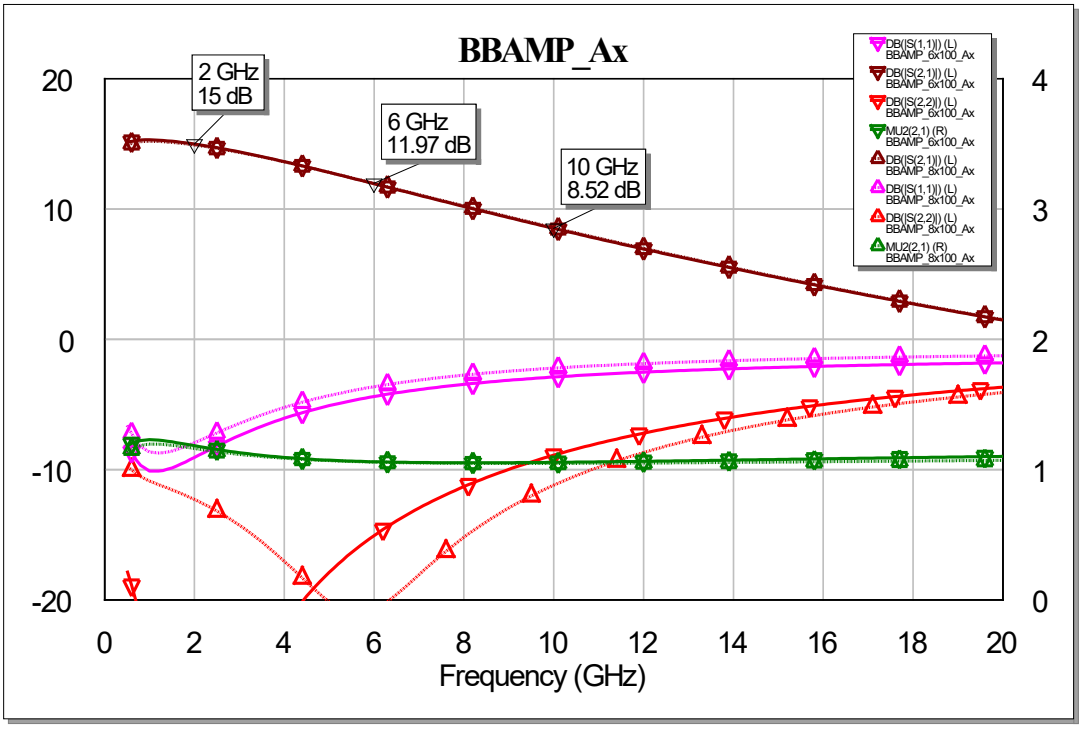

Fig. 8 S-parameters of 6- and 8- × 100-µm broadband feedback amplifiers

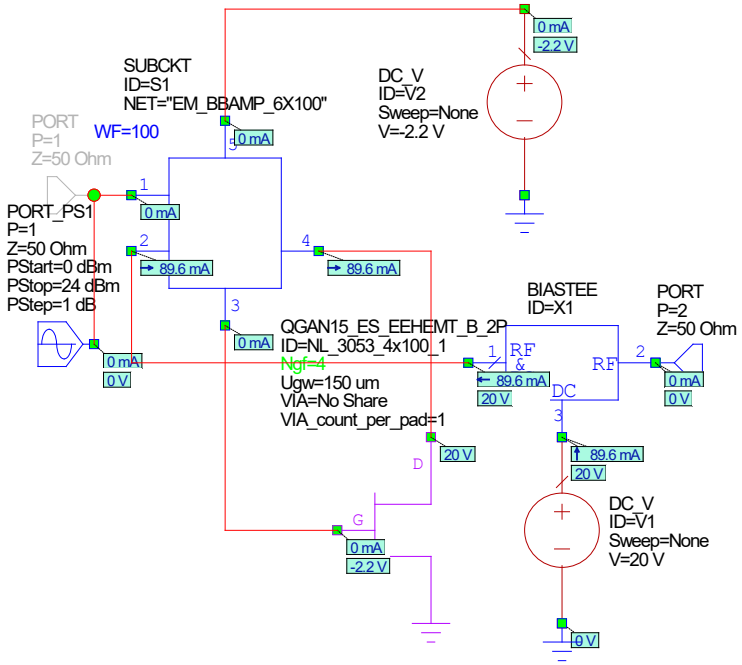

Fig. 9 Schematic of 6- × 100-µm broadband feedback amplifier (uses EM simulation of layout)

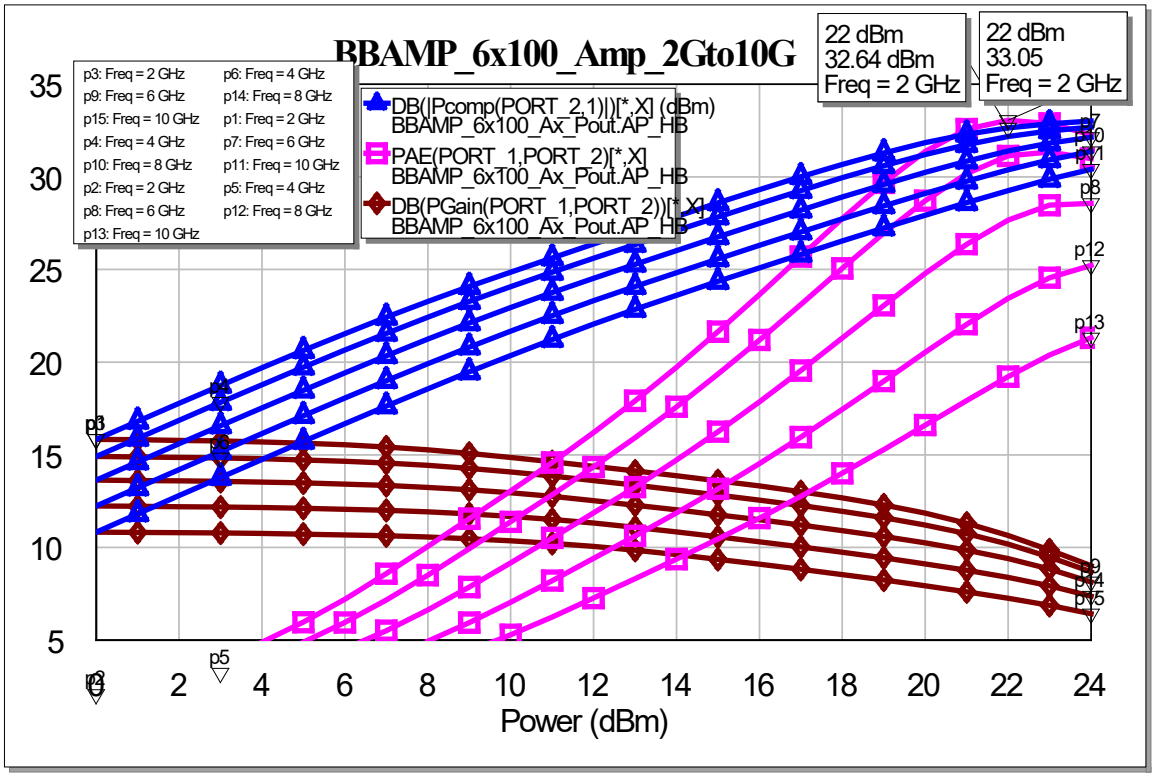

Fig. 10 Power performance of 6- × 100-µm broadband feedback amplifier (20 V, 2–10 GHz)

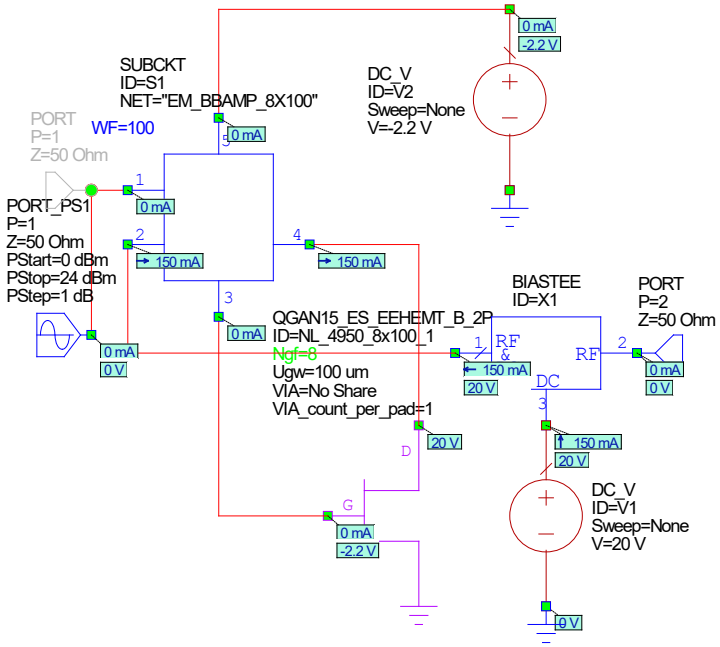

Fig. 11 Schematic of 8- × 100-µm broadband feedback amplifier (uses EM simulation of layout)

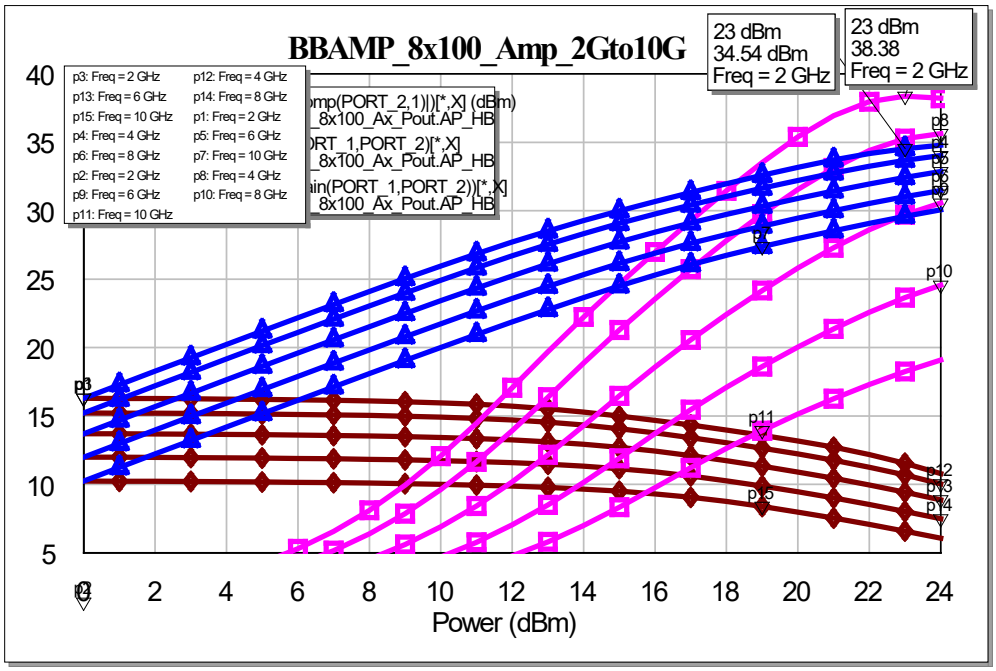

Fig. 12 Power performance of 8- × 100-µm broadband feedback amplifier (20 V, 2–10 GHz)

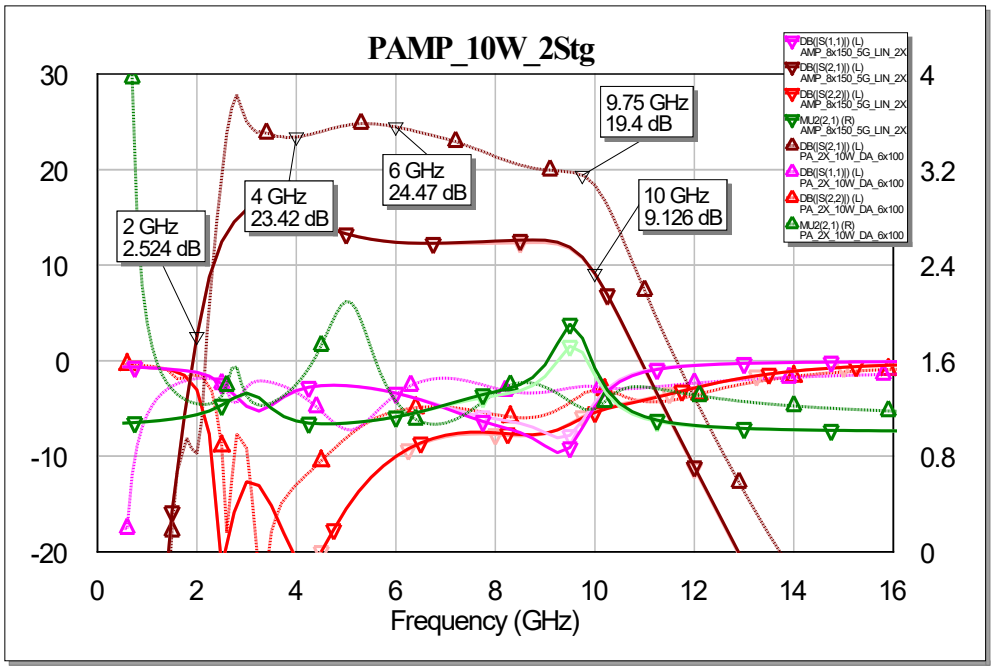

Fig. 13 S-parameters of two-stage (dash) vs. one-stage (solid) 10-W PA

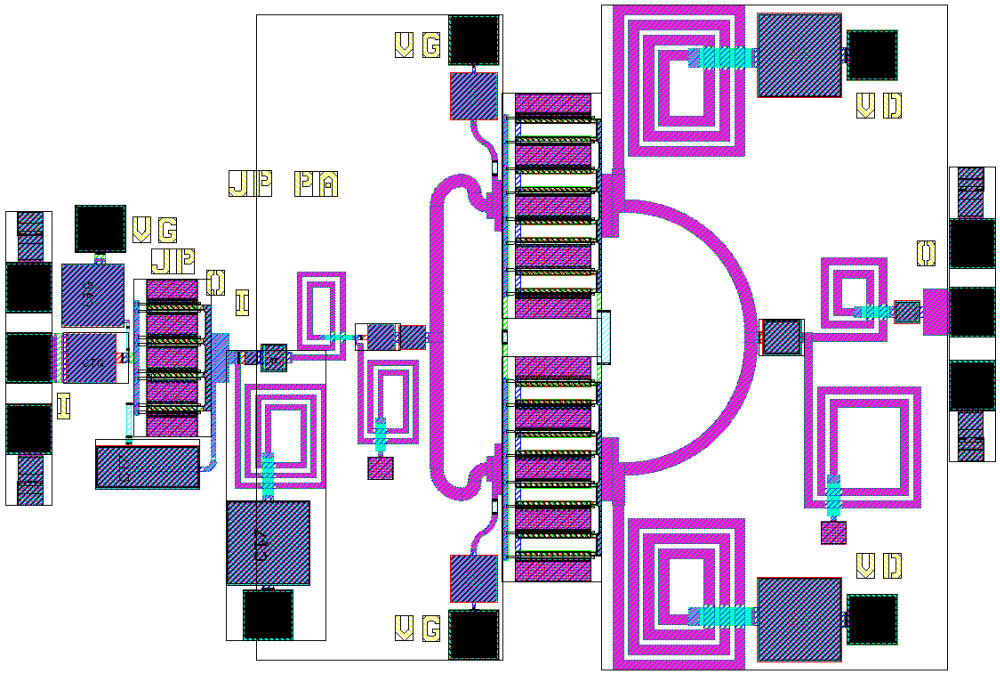

Fig. 14 Layout of two-stage 10-W PA (8- × 100-µm driver, 2× 8- × 150-µm output)

4. Broadband Feedback Amplifiers Design

The feedback amplifiers for the driver stage of the previous two-stage PA were added as stand-alone test circuits in a small 2.15- × 1.0-mm die site (Fig. 15). The simulations of the 6- and 8- × 100-µm broadband amplifiers were shown previously. Included in the die space is the stand-alone 8- × 100-µm amplifier and an 8- × 100-µm amplifier with the added LPF, which is the driver stage design of the prior two-stage S- to X-band 10-W PA. An s-parameter simulation of the 8- × 100-µm broadband amplifier with and without the LPF on the output is shown in Fig. 16.

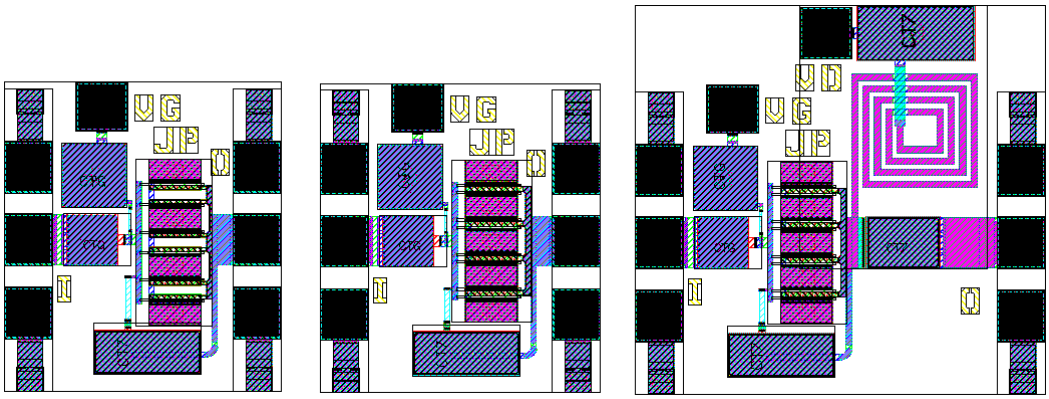

Fig. 15 Layout of broadband feedback amplifiers 2.15- × 1.0-mm die (6 × 100 µm, 8 × 100 µm, and 8 × 10 µm + LPF)

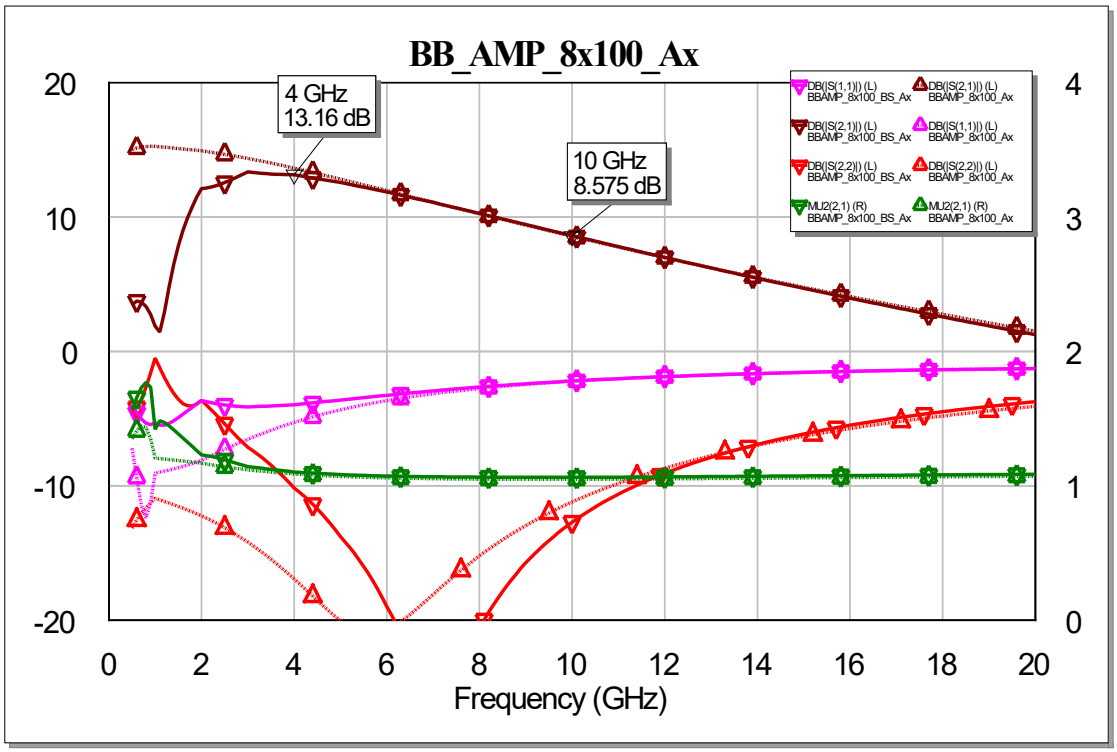

Fig. 16 S-parameters of 8 × 100 µm (dash) and 8 × 100 µm + LPF (solid) broadband feedback amplifiers

5. Balun and 12- to 24-GHz PA

A PA for 12- to 24-GHz operation, a broadband Ka-band balun, a test 8- to 75-µm HEMT, and a test "Thru" line were part of a 3.925- × 1-mm die site (Fig. 17). The balun was based on a design that Sami Hawasli, of the DEVCOM Army Research Laboratory team, had for a different GaN process, but which was easy to translate to the Qorvo 0.15-µm GaN-on-silicon carbide process. An input (right side) to the balun should be split equally in power to the two outputs (left side) with a 180° phase difference between them. This balun will be used in another frequency-doubler circuit also included in this fabrication for the GaN RF Challenge.

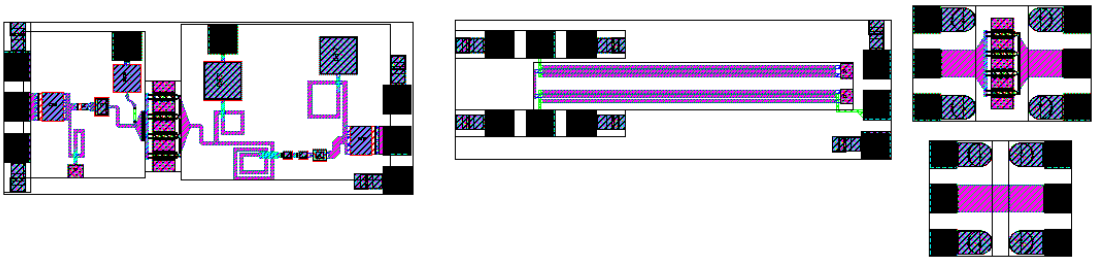

Fig. 17 Layout of broadband PA, broadband balun 3.925- × 1-mm die (test 8- × 75-µm HEMT, Thru)

A PA for 12- to 24-GHz operation was designed starting with load pull for a 0.25-mm (4- × 62-µm) HEMT at 10, 20, and 30 GHz. The schematic for the load pull is shown in Fig. 18, which results in load-pull contours for peak power and efficiency at 10 and 20 GHz (Figs. 19 and 20). These load-pull contours were used to determine a parallel resistor–capacitor (RC) model of the ideal power match, which was then scaled to a larger 8- × 75-µm HEMT for the PA design. Because the output match of a PA is critical to its performance, a broadband double-tuned match was designed for a center frequency of 17 GHz with the goal of 12- to 24-GHz bandwidth. Ideal lossless elements were used for the initial design (Fig. 21), then an equivalent output match using the lossy MMIC elements were created. The layout of the MMIC output match is shown in Fig. 22, and its performance relative to the lossless ideal output match is shown in Fig. 23. Some loss is expected in the physical implementation, but this plot shows that the losses are quite high at 13 and 23 GHz, meaning the 12- to 24-GHz bandwidth goal for power performance will not be met. It will likely work well over some range in the middle of the band.

An ideal lossless broadband input match was designed, using a parallel RC to stabilize the PA at lower frequencies where gain is higher while maximizing gain at the higher end of the band. Figure 24 shows the lossless input match, which is converted into a MMIC layout shown in Fig. 25. A simulation of the ideal lossless PA shows the potential gain bandwidth, which exhibits the typical decreasing gain slope with frequency (Fig. 26). Final simulation of the lossy MMIC broadband PA has a similar, but slightly lower gain slope, as shown in Fig. 27. The result appears to be less than the desired goal of 12–24 GHz; however, the PA should work well over a broad band around the 17-GHz center frequency. When the fabricated design is tested, its performance and potential for an improved future redesign will be evaluated.

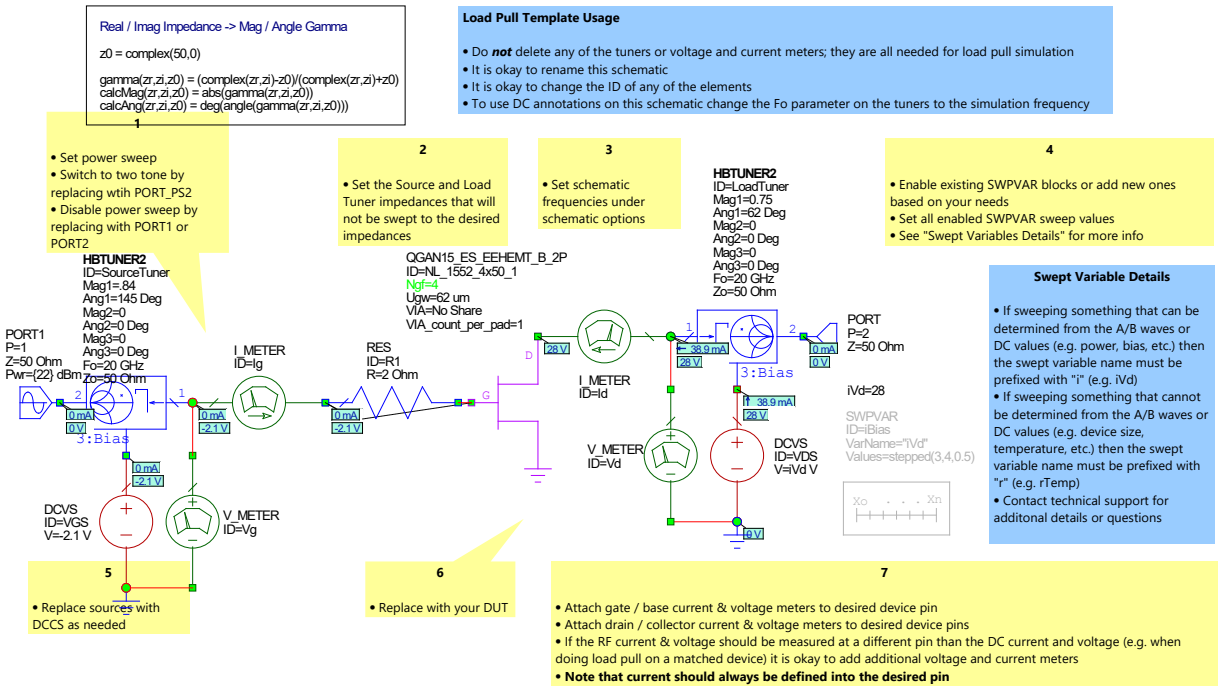

Fig. 18 MWO load load-pull schematic (4- × 62-µm HEMT)

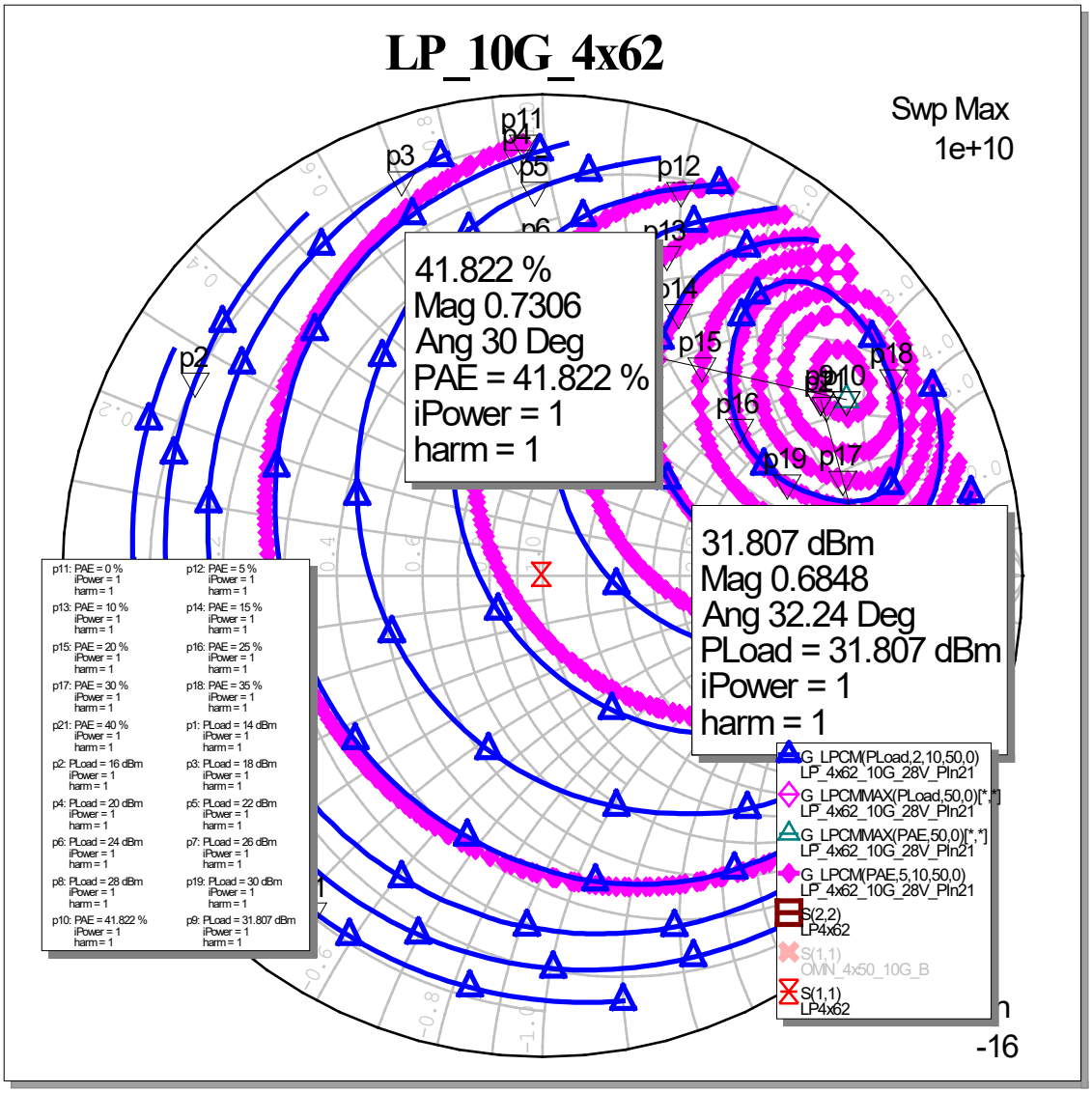

Fig. 19 Power-added efficiency (PAE) load-pull contours (4- × 62-µm HEMT, 10 GHz, 28 V)

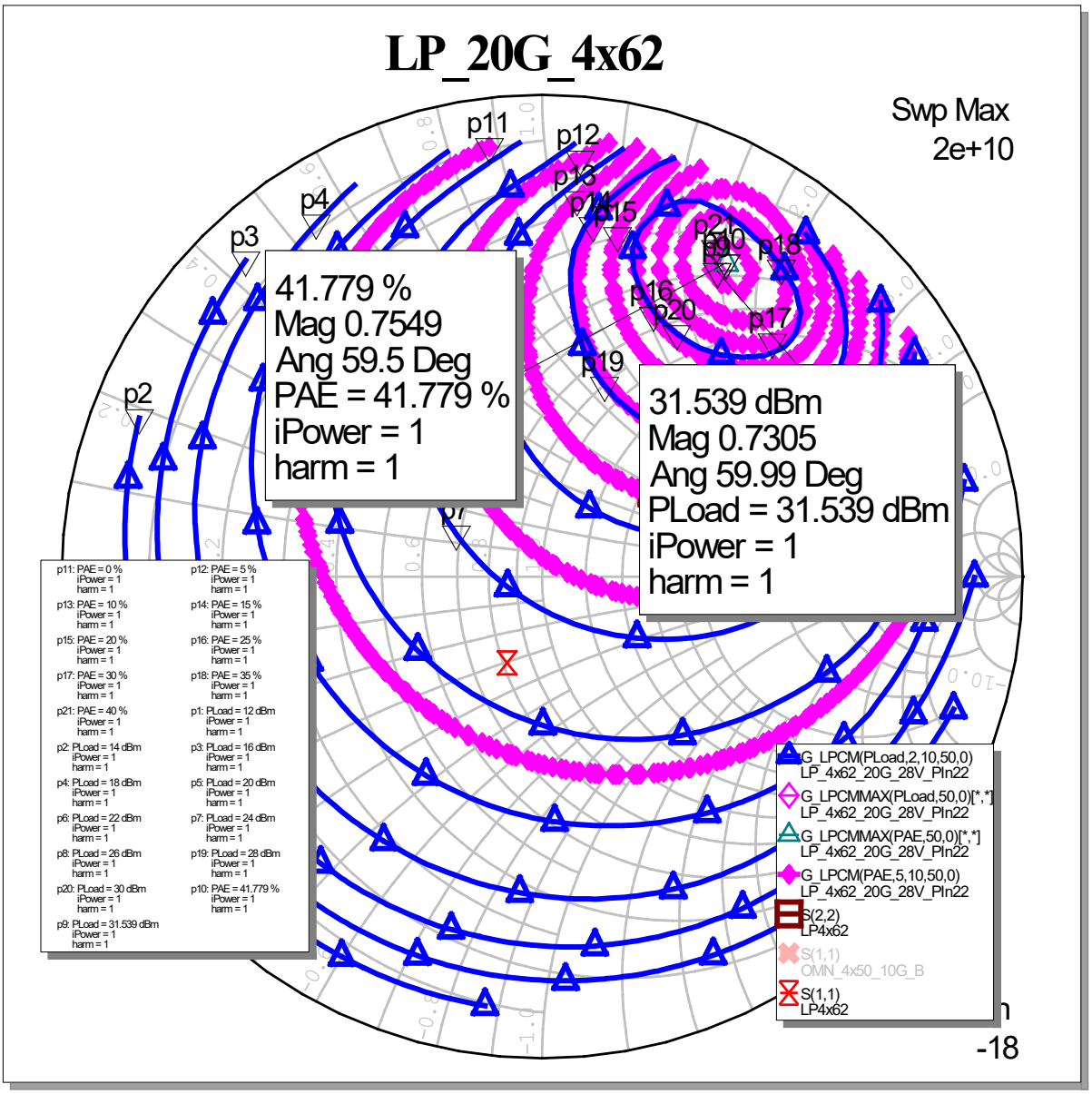

Fig. 20 PAE load-pull contours (4- × 62-µm HEMT, 20 GHz, 28 V)

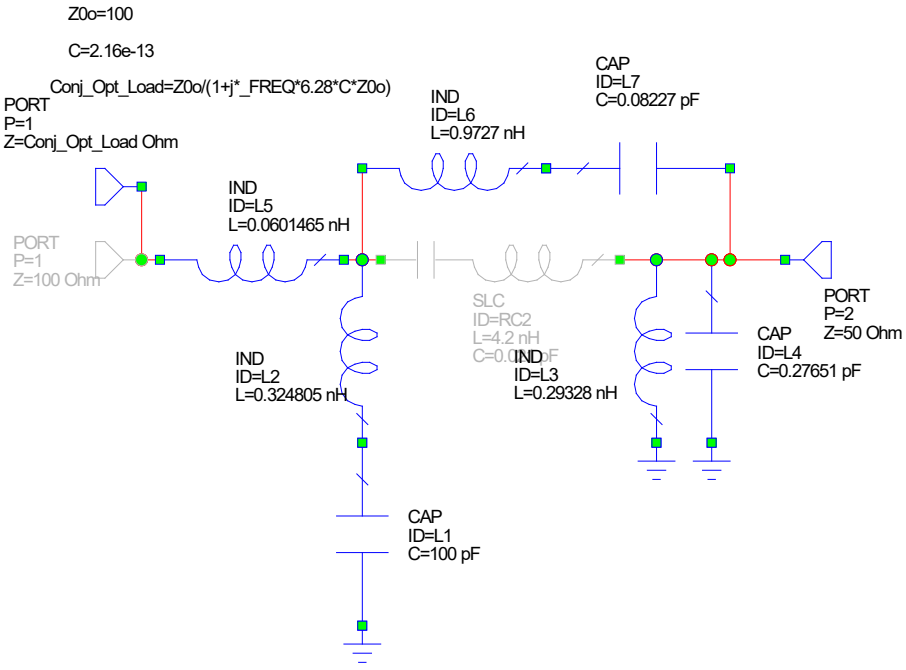

Fig. 21 MWO ideal lossless output match schematic (8- × 75-µm HEMT)

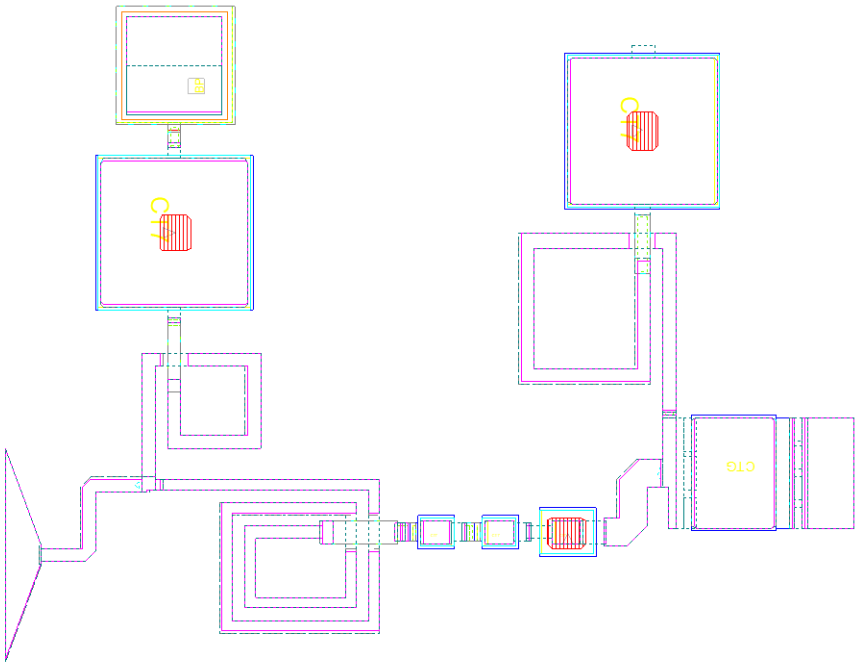

Fig. 22 MWO lossy MMIC output match layout (8- × 75-µm HEMT)

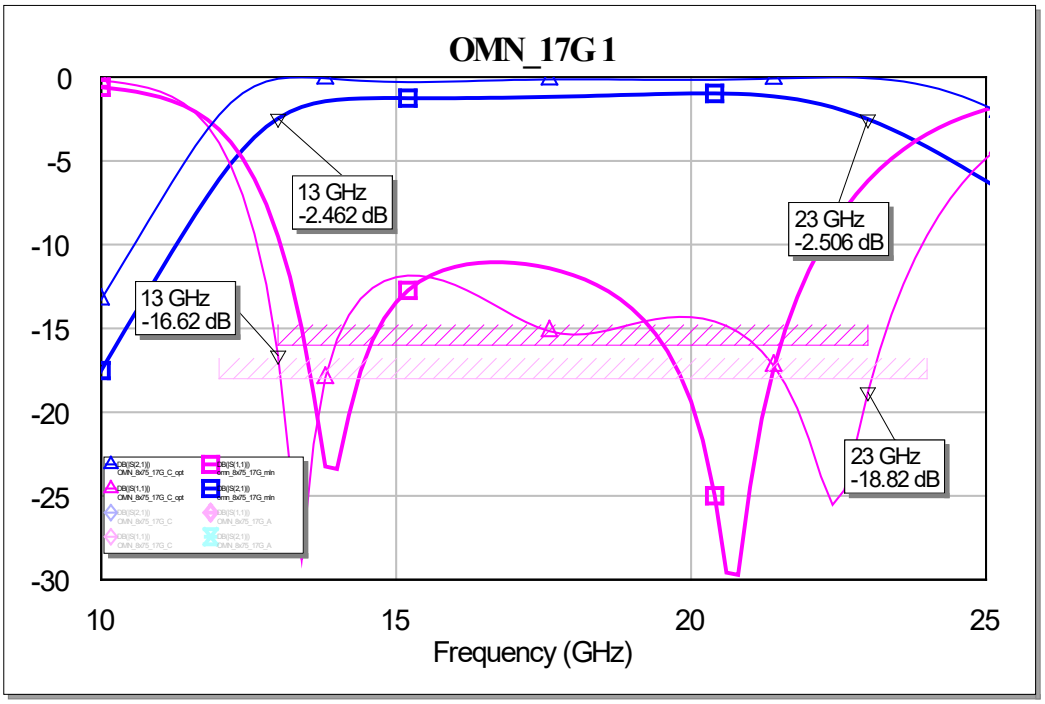

Fig. 23 Simulation of ideal (thin) vs. MMIC (thick) output match to ideal power load (8- × 75-µm HEMT)

An ideal lossless broadband input match was designed, using a parallel RC to stabilize the PA at lower frequencies where gain is higher while maximizing gain at the higher end of the band. Figure 24 shows the lossless input match, which is converted into a MMIC layout shown in Fig. 25. A simulation of the ideal lossless PA shows the potential gain bandwidth, which exhibits the typical decreasing gain slope with frequency (Fig. 26). Final simulation of the lossy MMIC broadband PA has a similar, but slightly lower gain slope, as shown in Fig. 27. The result appears to be less than the desired goal of 12–24 GHz; however, the PA should work well over a broad band around the 17-GHz center frequency. When the fabricated design is tested, its performance and potential for an improved future redesign will be evaluated.

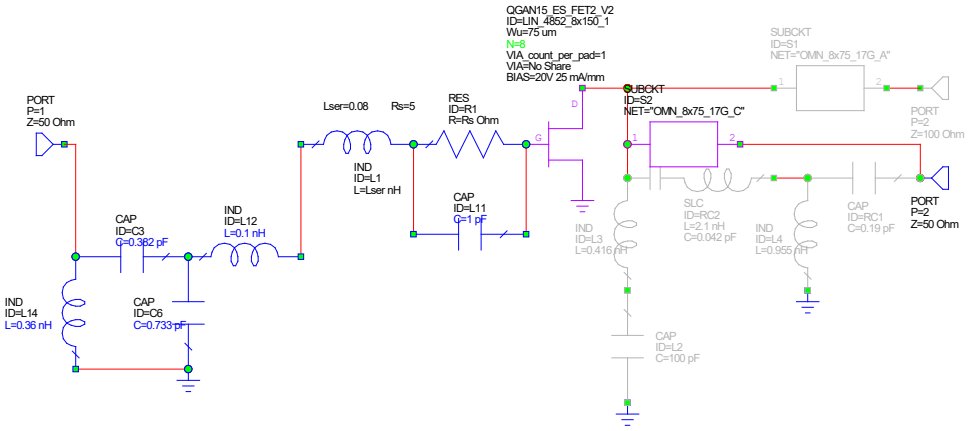

Fig. 24 MWO schematic of broadband 12- × 24-GHz, 8- × 75-µm PA with ideal lossless matching

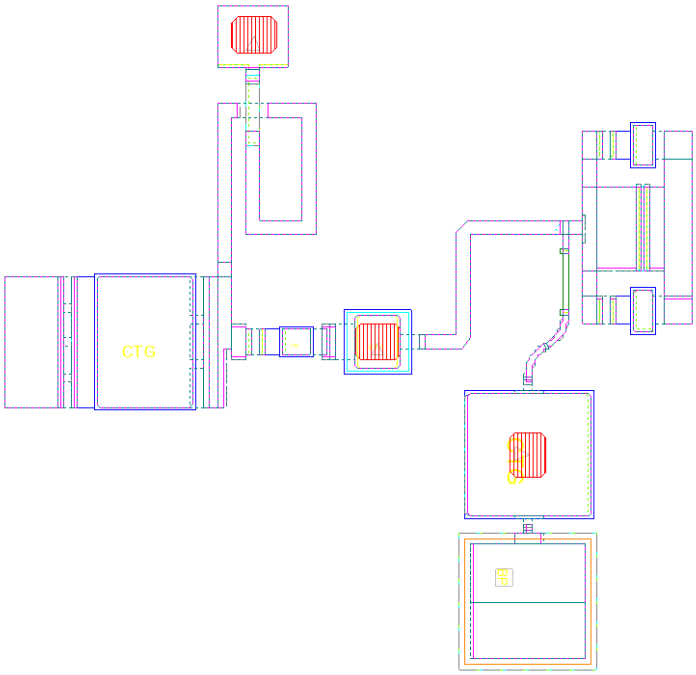

Fig. 25 MWO lossy MMIC input match layout 8- × 75-µm, 12- to 24-GHz PA

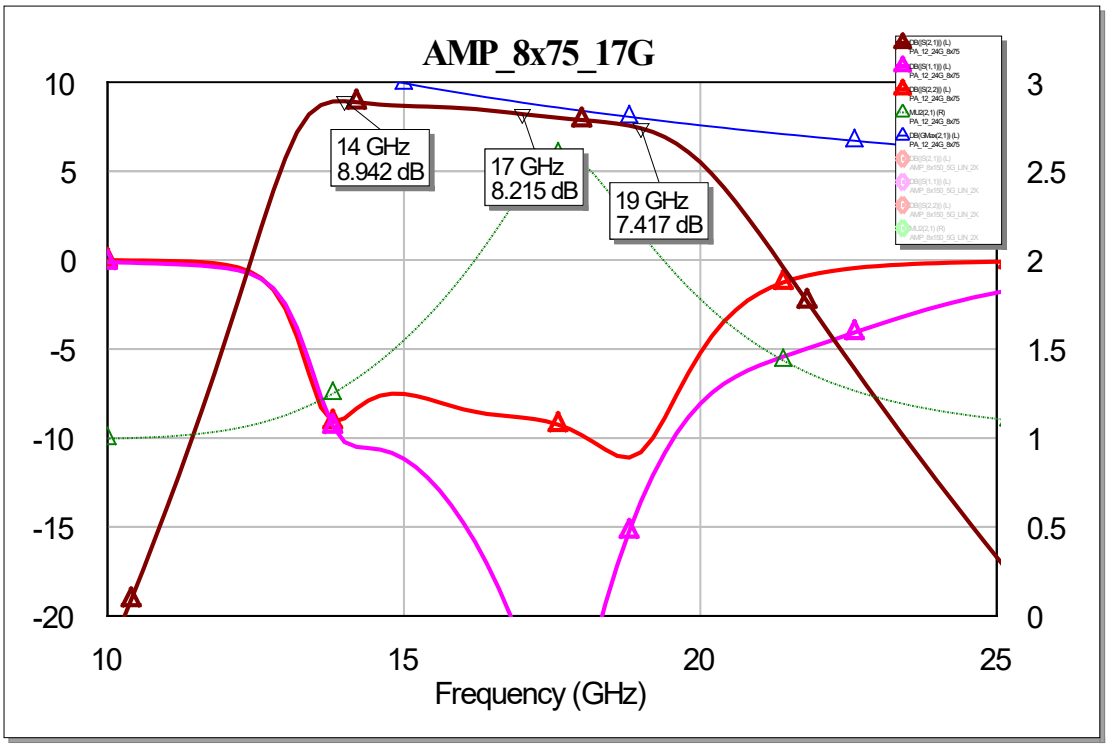

Fig. 26 S-parameter simulation of ideal broadband 8- × 75-µm, 12- to 24-GHz PA

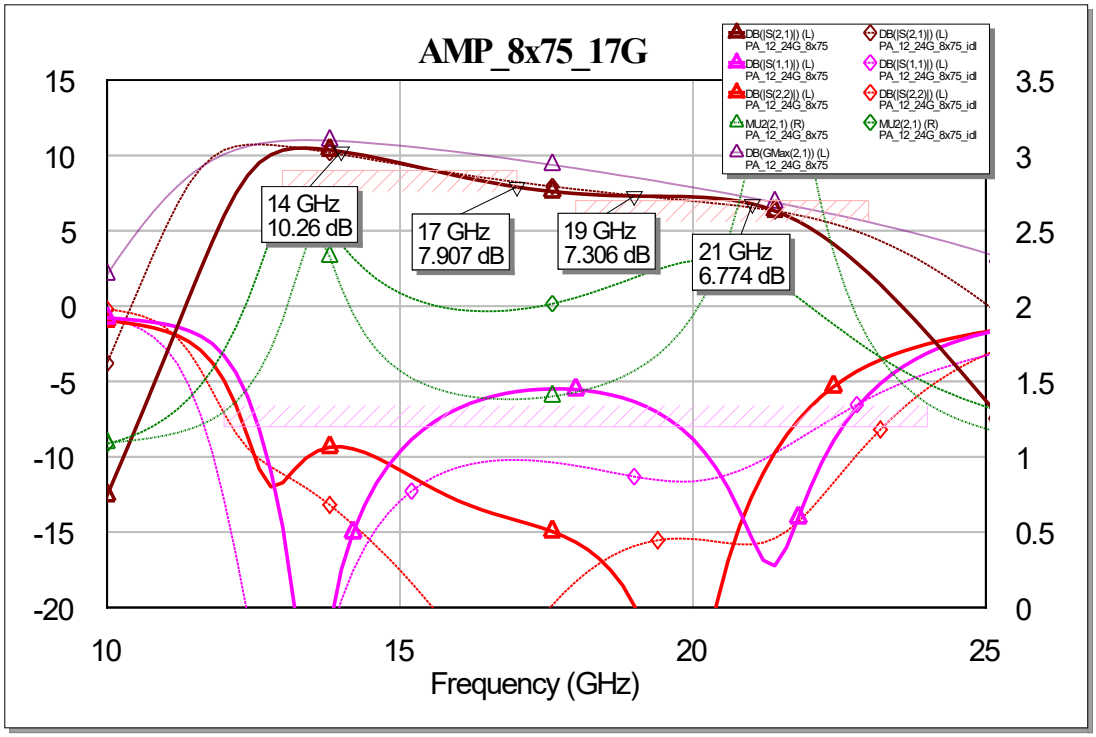

Fig. 27 S-parameter simulation of final MMIC broadband 8- × 75-µm, 12- to 24-GHz PA

6. Frequency-Doubler, 28–56 GHz

A broadband frequency-doubler topology using a balun was suggested by Dr Ali Darwish, of the ARL team, using the modified balun designed Sami Hawasli for Ka-band. The final 3.925- × 1-mm die site (Fig. 28) contains a broadband frequency-doubler with a smaller subcircuit frequency-doubler and two test HEMTs—a 4- × 50-µm HEMT and an 8- × 150-µm HEMT. Due to the limited design time, the doubler demonstration borrowed from prior designs around 28 GHz.[3] A new, simple, output match around 56 GHz was designed to be used with the existing 28-GHz low-noise amplifier design. Simulations verified that the circuit should work well. Two of these doubler subcircuits were then parallel-combined using the balun and a broadband Wilkinson coupler (60 GHz), the latter simulated using Axiem EM, showing a comparison between the original linear simulation and the EM simulation in Fig. 29. The broadband doubler consists of the broadband balun, the Wilkinson combiner, and two parallel copies of the 28- to 56-GHz doubler subcircuit connected as shown in the layout plot of Fig. 30. Each of the components of the doubler were Axiem EM-simulated and used for a nonlinear simulation whose schematic is shown in Fig. 31. A comparison of the nonlinear simulation of the basic doubler and the fundamental cancelling doubler (with balun) is shown in Figs. 31 and 32. Figure 31 shows the cancelling of the 28-GHz input signal due to the use of the balun, which is further emphasized by the spectrum plot of Fig. 32. Measurements of the fabricated circuit will demonstrate this topology, which could be modified or redesigned for future uses.

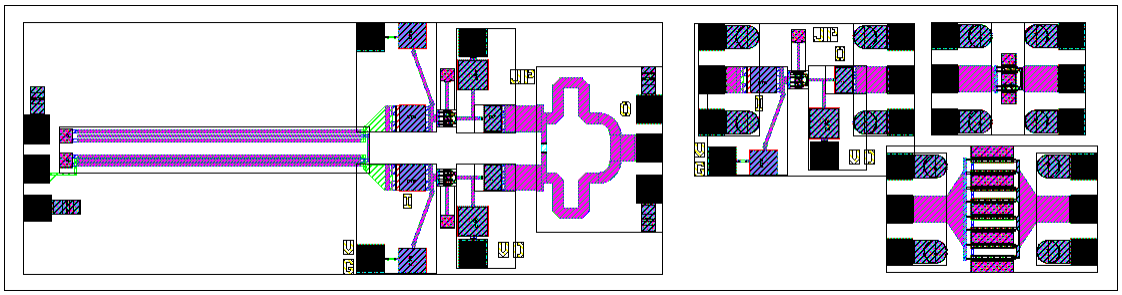

Fig. 28 Layout of broadband frequency-doubler and doubler subcircuit 3.925- × 1-mm die (4- × 50-µm and 8- × 150-µm test HEMTs)

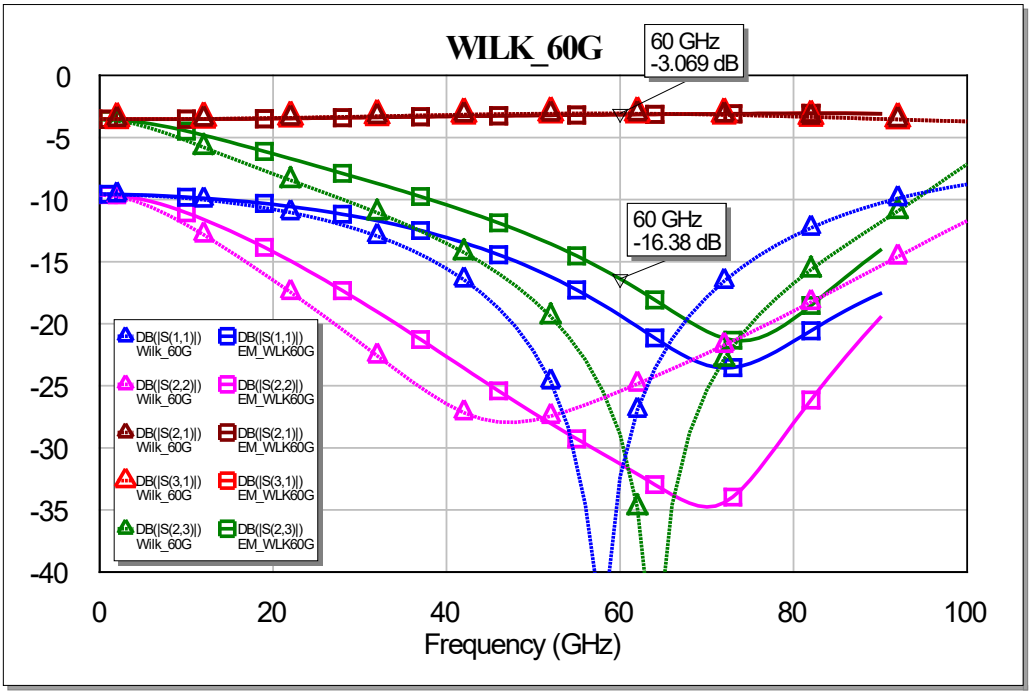

Fig. 29 Wilkinson 60-GHz coupler simulation linear (dash) vs. EM (solid)

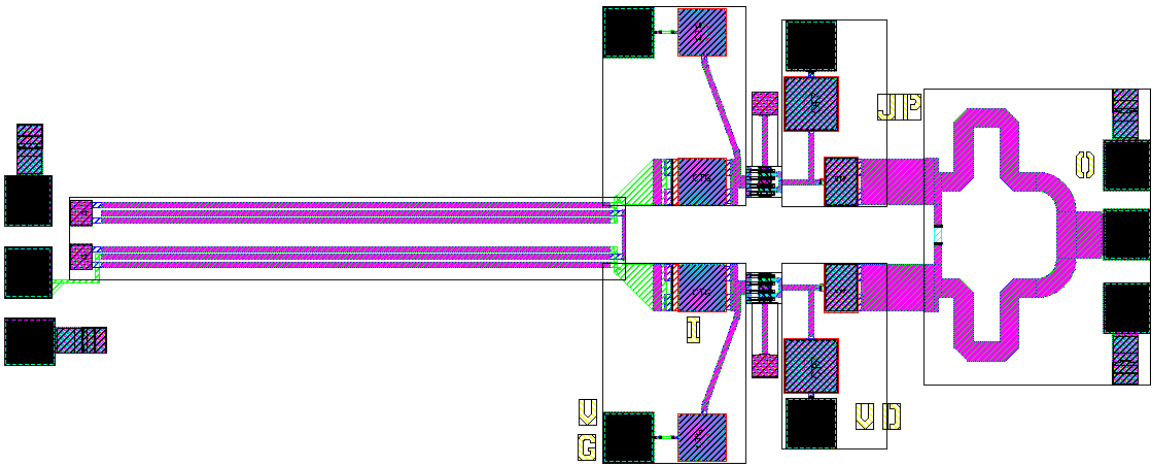

Fig. 30 Broadband frequency-doubler layout

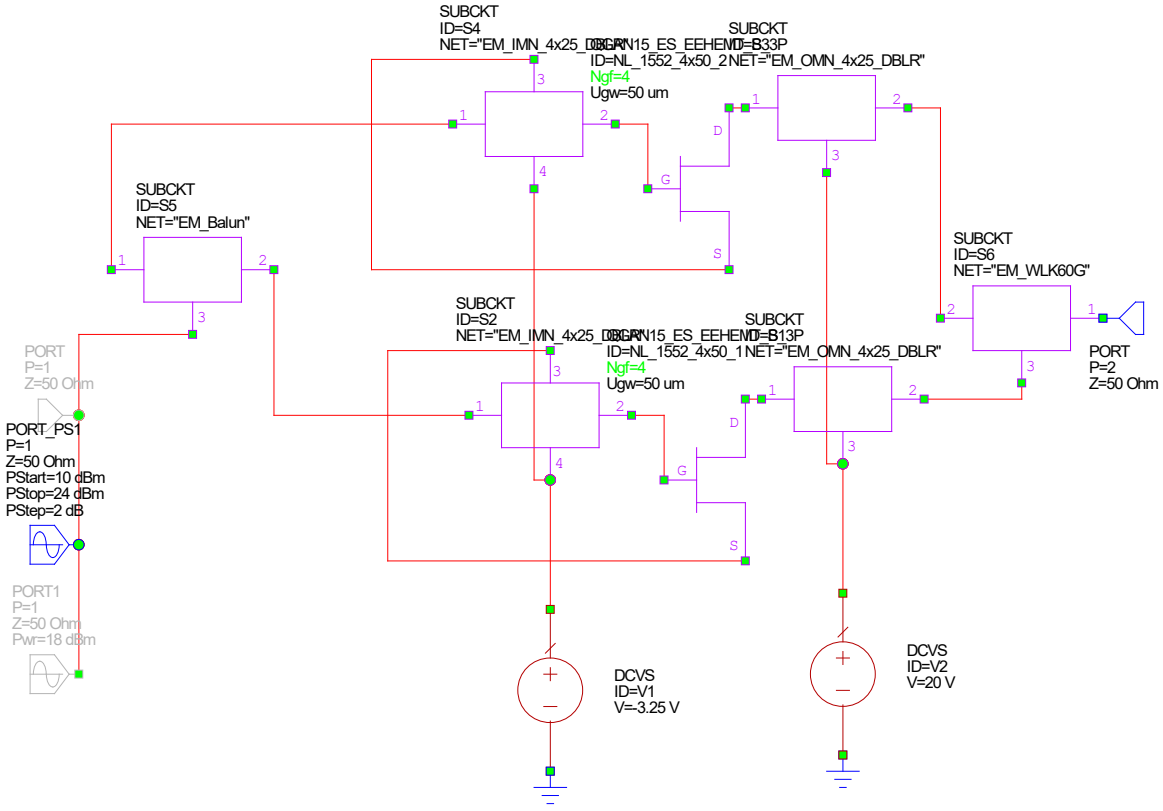

Fig. 31 Schematic of broadband frequency-doubler (uses EM simulations of layout)

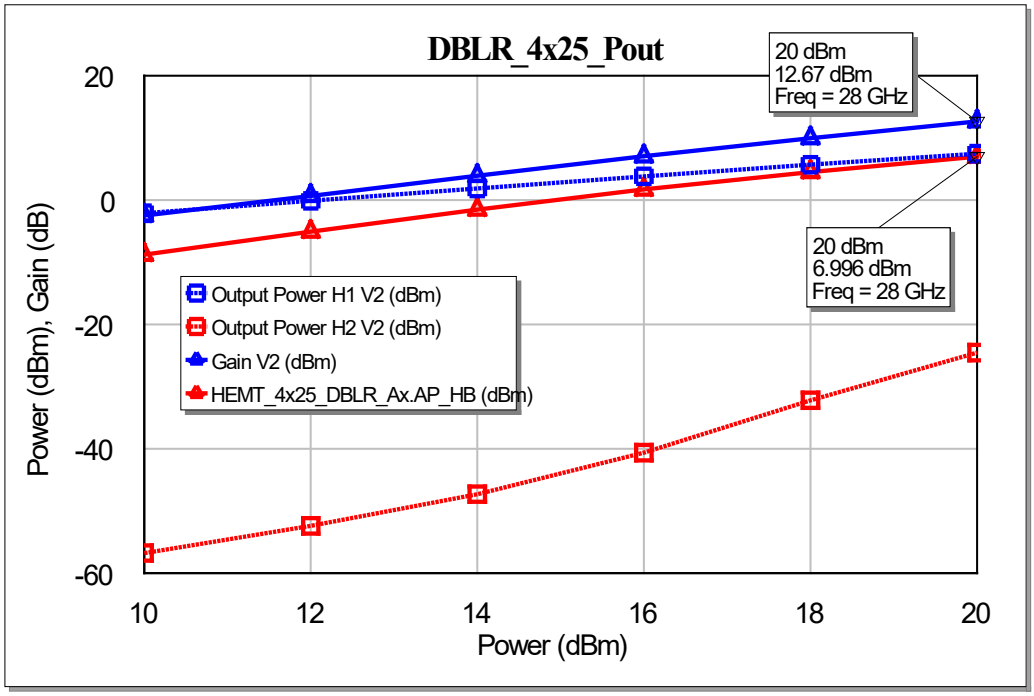

Fig. 32 Harmonic performance of frequency-doublers vs. input power

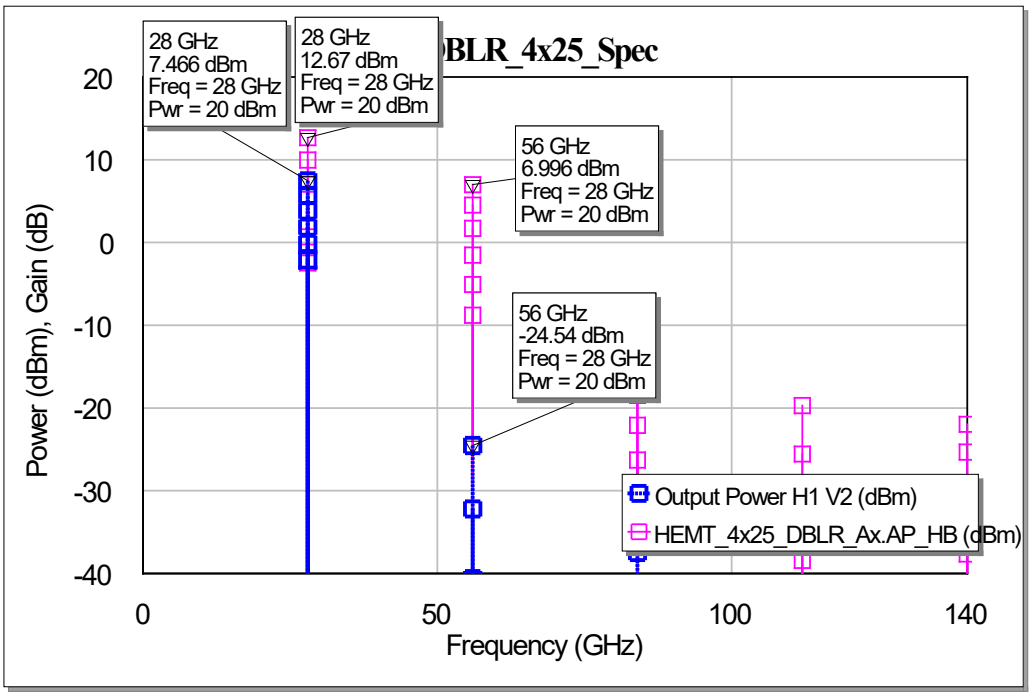

Fig. 33 Spectrum plot of frequency-doublers simulation

7. GaN RF Challenge Submission

The DOD teams portion of the Qorvo 0.15-µm GaN reticle for the GaN RF Challenge was used for several ARL-designed circuits, as shown in Fig. 34. Die site sizes were two 2.15 × 3 mm, two 3.925 × 1 mm, and one small corner of 2.15 × 1 mm. Circuit designs were described in the prior sections and will be tested starting sometime in 2021 after the fabrication is completed.

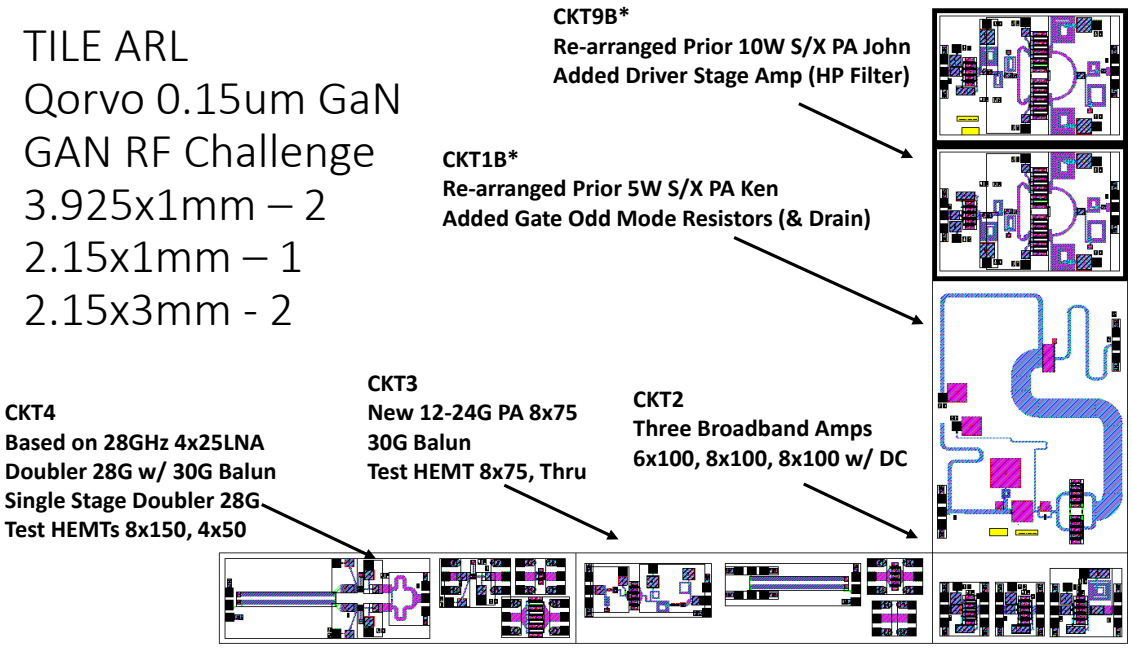

Fig. 34 ARL designs for DOD teams sites for GaN RF challenge (Qorvo 0.15-µm GaN)

8. Conclusions

The GaN RF Challenge effort included many teams exploring challenges focused on the broadband 5G development and DOD electronic warfare needs. Parallel fabrication efforts using BAE's 0.18-µm GaN process and Qorvo's 0.15-µm GaN process will consolidate and produce multiple design-team efforts, with die to be returned in 2021 for test. Our ARL III/V Team was primarily focused on the BAE design effort, but was also able to use the available space of the DOD design teams for the Qorvo fabrication. These designs used prior experience and efforts from the ARL III/V team to quickly assemble useful circuits to fabricate in the Qorvo process. Some circuits were improvements to prior designs, such as adding an extra gain stage to a broadband S- to X-band 10-W PA or a redesign of a dual-band S-/X-band 5-W PA to remove an odd-mode stability issue. Other circuits were new designs to prove-out concepts like a Ka-band frequency-doubler and other broadband PA designs. When the designs return, they will be tested, evaluated, and documented for future use and incorporation into DOD needs.

9 References

1. Penn J, Darwish A, Hawasli S, McKnight KJ. Gallium nitride high-electron-mobility transistor (HEMT) monolithic microwave integrated circuit (MMIC) designs submitted for Qorvo prototype wafer option (PWO) fabrication. DEVCOM Army Research Laboratory; 2019 Nov. Report No.: ARL-TR-8811.

2. Penn J. Low-noise amplifiers (LNAs) and power amplifiers (PAs) for next-generation S- and X-band radars. DEVCOM Army Research Laboratory; 2019 Dec. Report No.: ARL-TR-8871.

3. Penn J, Darwish A. Ka-band front-end monolithic microwave integrated circuits (MMICs) and transmit–receive (T/R) modules. DEVCOM Army Research Laboratory; 2019 Nov. Report No.: ARL-TR-8855.

List of Symbols, Abbreviations, and Acronyms

5G	fifth generation
ARL	Army Research Laboratory
CAD	computer-aided design
DC	direct current
DEVCOM	US Army Combat Capabilities Development Command
DOD	Department of Defense
EM	electromagnetic
GaN	gallium nitride
HEMT	high electron mobility transistor
LPF	low-pass filter
MMIC	monolithic microwave integrated circuit
MWO	Microwave Office (computer-aided design tool)
PA	power amplifier
PAE	power-added efficiency
RC	resistor–capacitor
RF	radio frequency

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