ARL-TN-0835● July 2017

US Army Research Laboratory

Gallium Nitride (GaN) Monolithic Microwave Integrated Circuit (MMIC) Designs Submitted to Air Force Research Laboratory (AFRL)-Sponsored Qorvo Fabrication

by John E Penn

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

The US Army Research Laboratory (ARL) is exploring devices and circuits for radio frequency communications, networking, and sensor systems of interest to Department of Defense applications, particularly for next-generation radar systems. Broadband, efficient, high-power MMIC amplifiers are extremely important in any communication system that must operate reliably and efficiently in continually crowded spectrums, with multiple purposes for communications, networking, and radar. This report briefly summarizes several designs using Qorvo's 0.25-µm high power, efficient, gallium nitride on 4-mil silicon carbide process that were submitted to an Air Force Research Laboratory-sponsored wafer fabrication.

15. SUBJECT TERMS

GaN, HEMT, MMIC, microwave, amplifier

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Acknowledgments

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1. Introduction

The US Army Research Laboratory (ARL) has been evaluating and designing efficient broadband linear high-power amplifiers for future adaptive multimode radar systems in addition to other applications such as communications, networking, and electronic warfare. Qorvo has a high-performance 0.25-µm gallium nitride (GaN) fabrication process and a process design kit that researchers at ARL used to design broadband amplifiers, power amplifiers (PAs), and other circuits for future radar, communications, and sensor systems. These ARL designs are to be submitted for fabrication as part of an Air Force Research Laboratory (AFRL)-led effort. These designs will demonstrate the performance, bandwidth, capability, versatility, and applicability of GaN for compact, efficient, monolithic microwave integrated circuit (MMIC) designs.

2. High-Power Couplers (GaN)

Passive couplers for combining high-power amplifier stages were designed in Qorvo's 0.25-µm GaN on silicon carbide (SiC) process. One concern for limitations in a passive combiner is the isolation resistor between the split ports. Several ideas were considered, settling on the Mesa Resistor as a good choice for high-power handling capability. Figures 1 and 2 show the layouts and simulations of a simple 1-stage 3- to 6-GHz Wilkinson coupler/combiner. A 2-stage broader band Wilkinson coupler was designed by Dana Sturzbecher of Qorvo, with some layout assistance from the author. A simulation and layout of that broadband up to 3-GHz coupler/combiner is shown in Figs. 3 and 4.

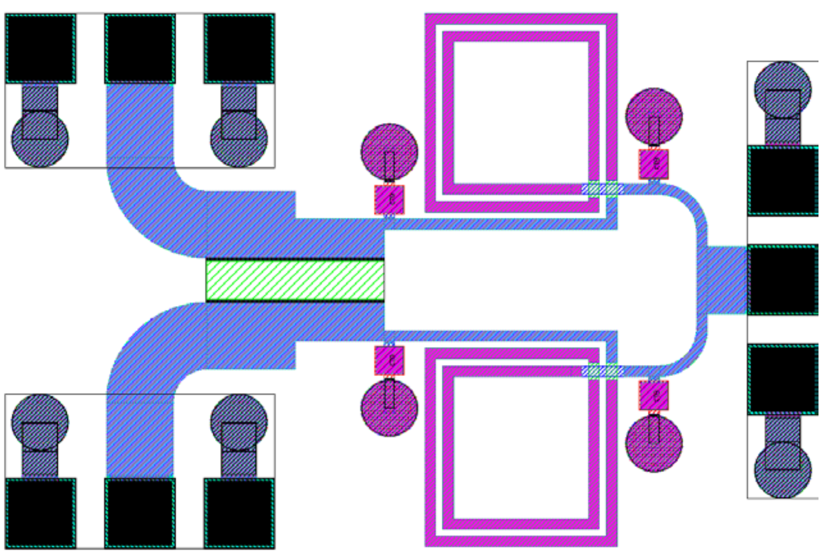

Fig. 1 Final layout of 3- to 6-GHz Wilkinson coupler Gen2 GaN (1.15 × 0.75 mm)

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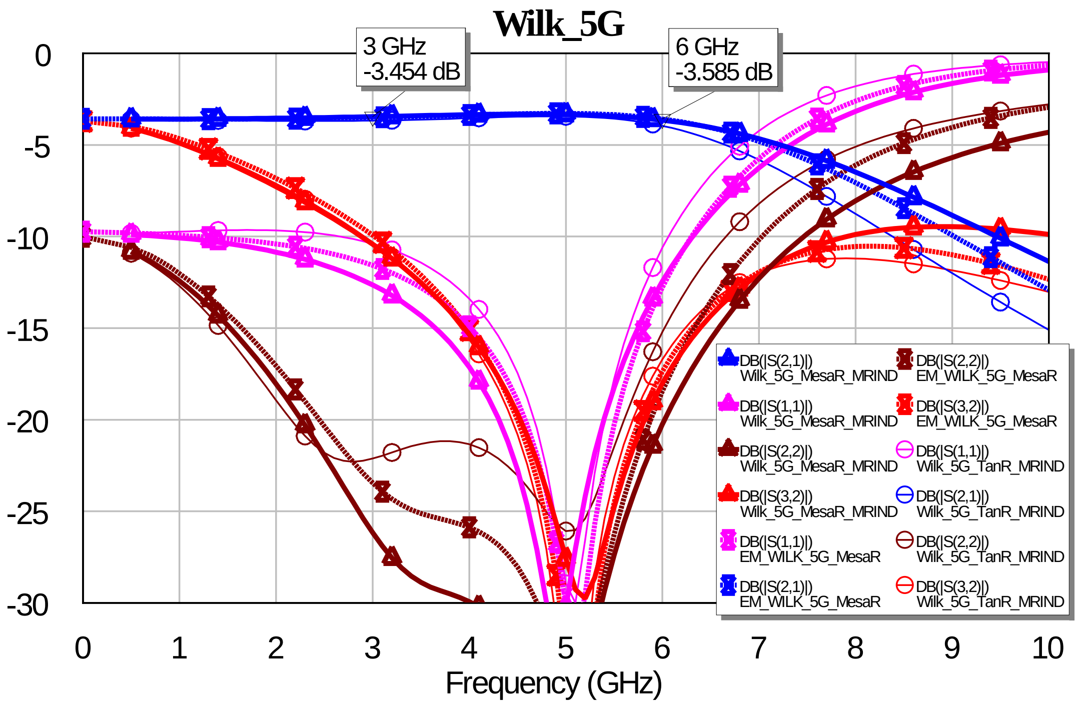

Fig. 2 Simulations of 3- to 6-GHz Wilkinson coupler Gen2 GaN (Microwave Office [MWO], Axiem electromagnetic [EM])

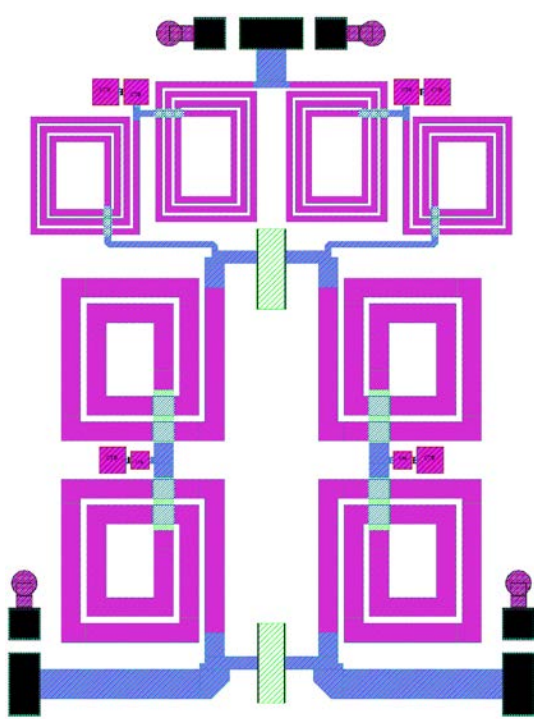

Fig. 3 Final layout of Dana Sturzebecher's 0.75- to 3-GHz Wilkinson coupler (1.7 × 2.2 mm)

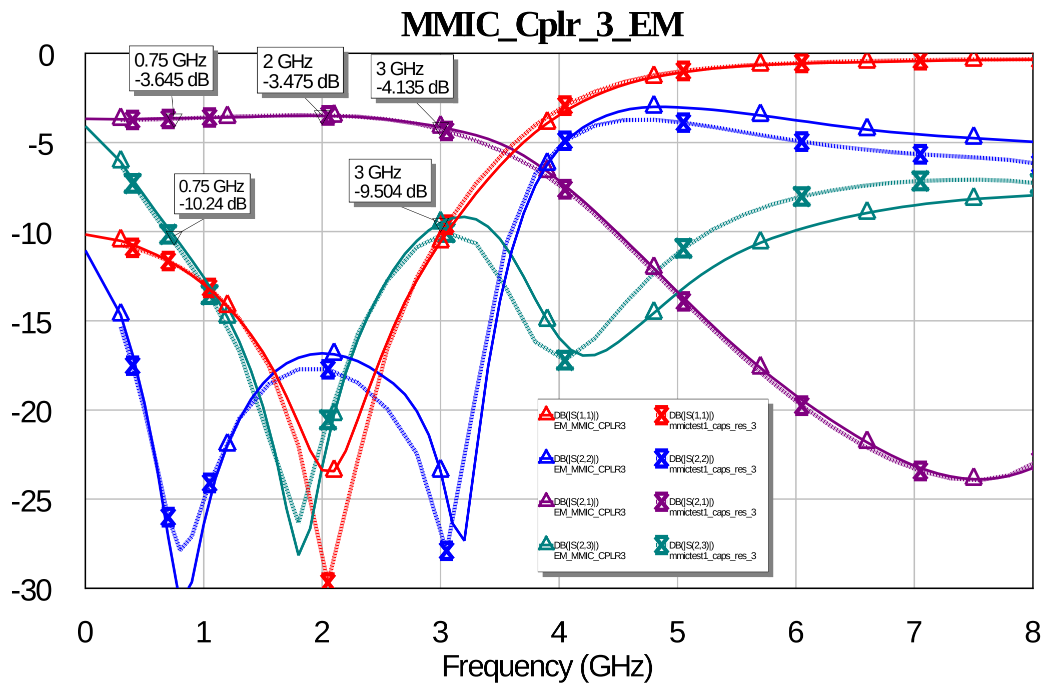

Fig. 4 Simulations of Dana Sturzebecher's 0.75- to 3-GHz coupler (MWO, Axiem EM)

3. Broadband High-Power Transmit/Receive (TR) Switches (GaN)

A broadband TR Single-Pull Double-Throw (SPDT) switch for operation up to 18 GHz was designed in Qorvo's 0.25-µm GaN on SiC process. The tradeoff of size, topology, and performance resulted in higher insertion loss than desired to achieve broadband performance up to 18 GHz. An earlier TR switch design had lower insertion loss but only operated up to 6 GHz, or so. Figures 5 and 6 show the layout and simulations of a broadband 0.1- to 18-GHz TR switch (SPDT).

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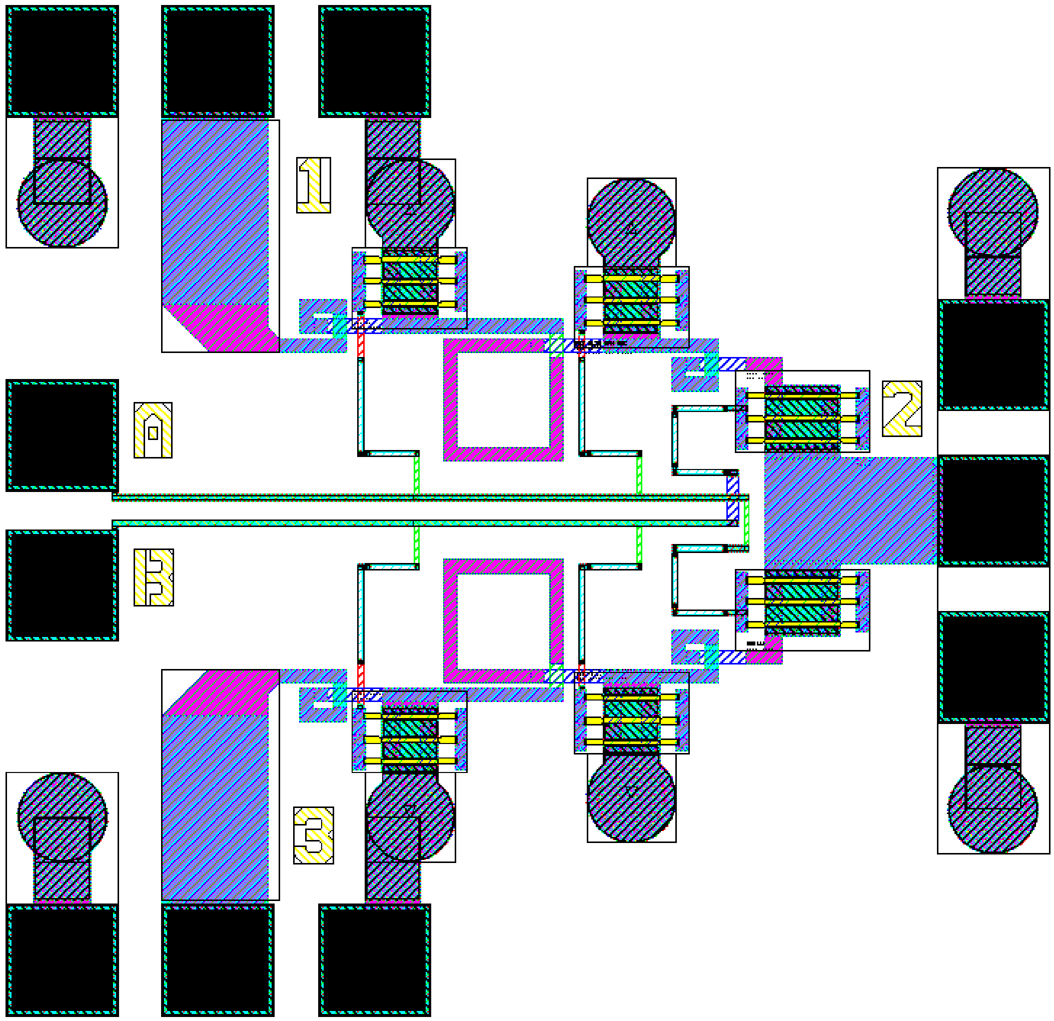

Fig. 5 Final layout of a broadband 0.3- to 18-GHz SPDT TR switch Gen2 GaN (0.9 × 0.9 mm)

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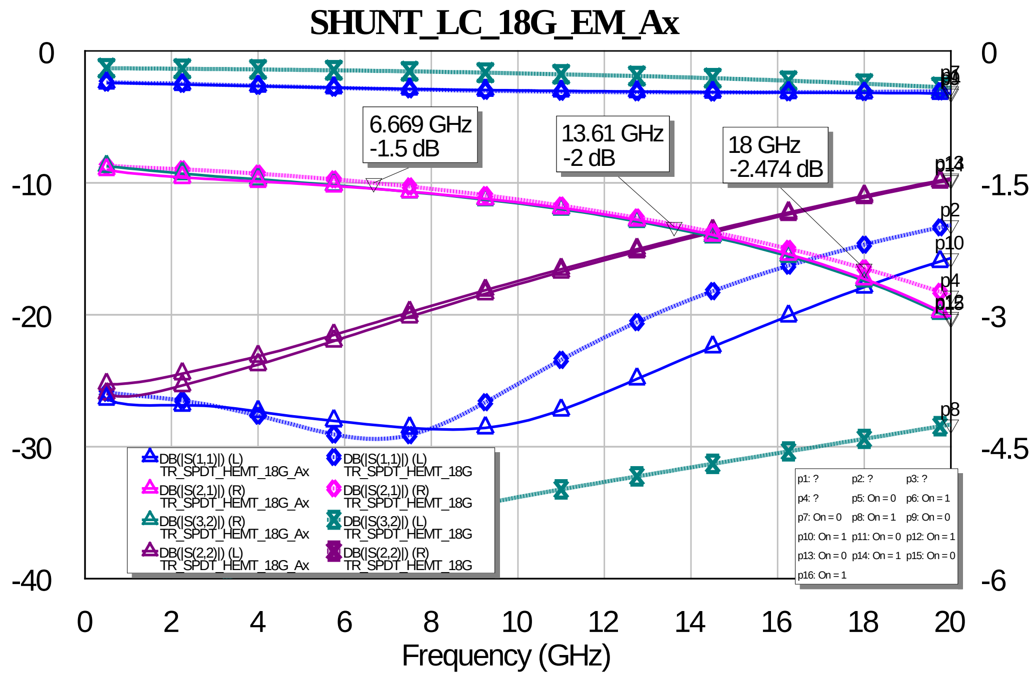

Fig. 6 Simulations of a broadband 0.3- to 18-GHz SPDT TR switch Gen2 GaN (MWO, Axiem EM)

4. Broadband High-Power Amplifiers (GaN)

A broadband 3- to 7-GHz 8-W PA was designed in Qorvo's 0.25-µm GaN on SiC process. Plots of the single-stage amplifier layout and simulation are shown in Figs. 7 and 8. To flatten the gain slope of the PA and increase the compressed gain above 20 GHz, a driver stage was added to the one stage design to create a slightly larger 3- to 7-GHz 8-W PA. Figures 9 and 10 show the layout and simulations of the broadband 3- to 7-GHz, 8-W, 2-stage PA. A flat small signal gain of about 25 dB is predicted from 4 to nearly 7 GHz for the 2-stage PA design. The simple, compact broadband feedback amplifier that serves as the first-stage driver for the 2-stage amplifier was submitted as a stand-alone compact test circuit for fabrication. Figures 11 and 12 show the layout and simulations of the broadband feedback amplifier. The gain of the feedback amplifier has the typical gain rolloff of III/V high-electron mobility transistors (HEMTs). In the 2-stage amplifier, additional passive matching elements were added between the feedback-amplifier driver stage and the final PA output stage to flatten the gain over the 3- to 7-GHz band.

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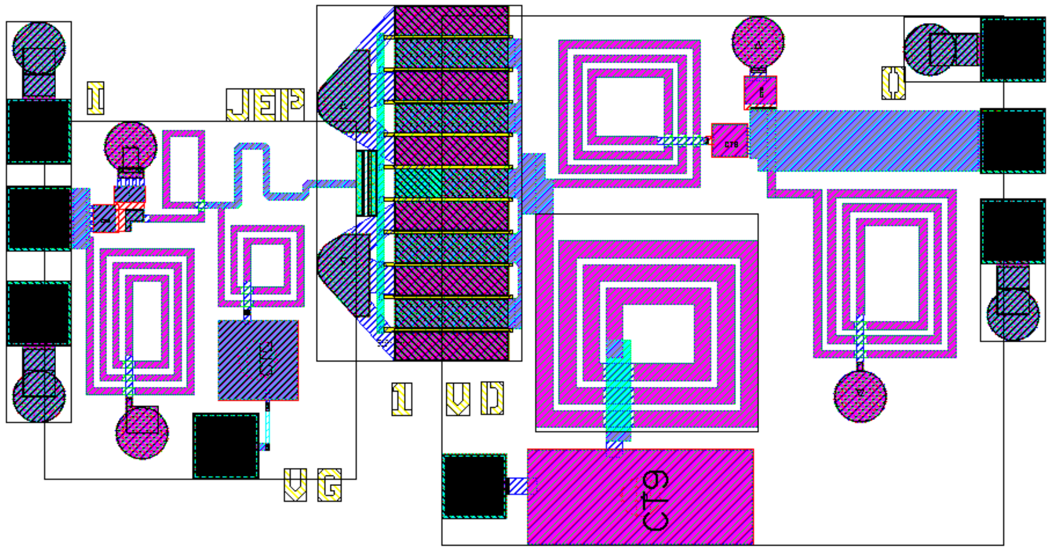

Fig. 7 Final layout of 8- to 10-W Gen2 1-stage (3- to 7-GHz) 1.75-mm GaN HEMT PA (1.6 × 0.8 mm)

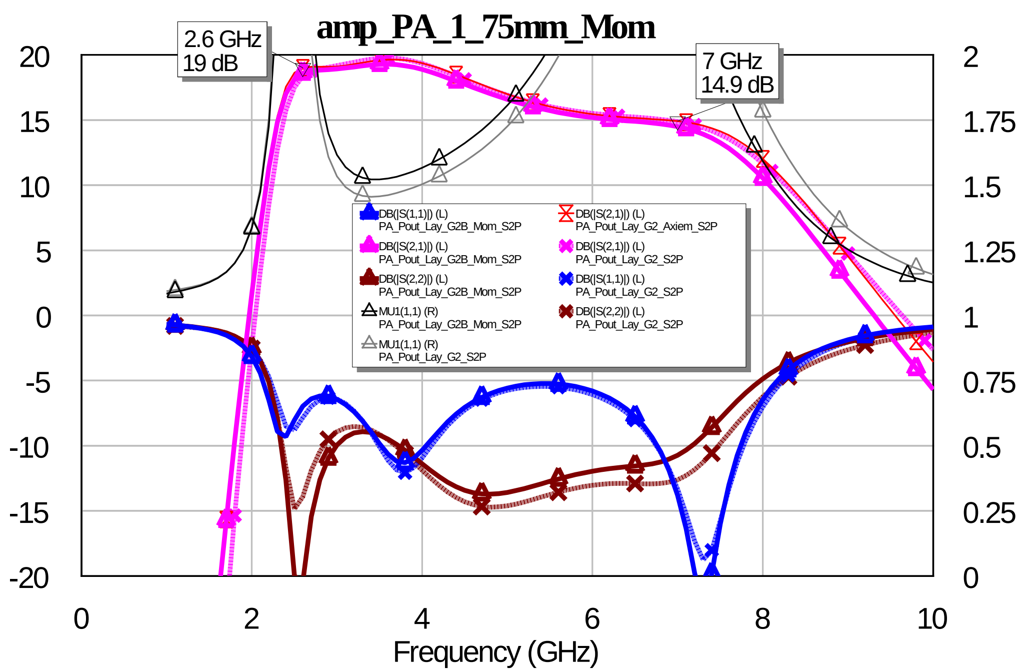

Fig. 8 Simulations of 8- to 10-W 1-stage (3- to 7-GHz) 1.75-mm GaN HEMT PA (MWO, momentum EM)

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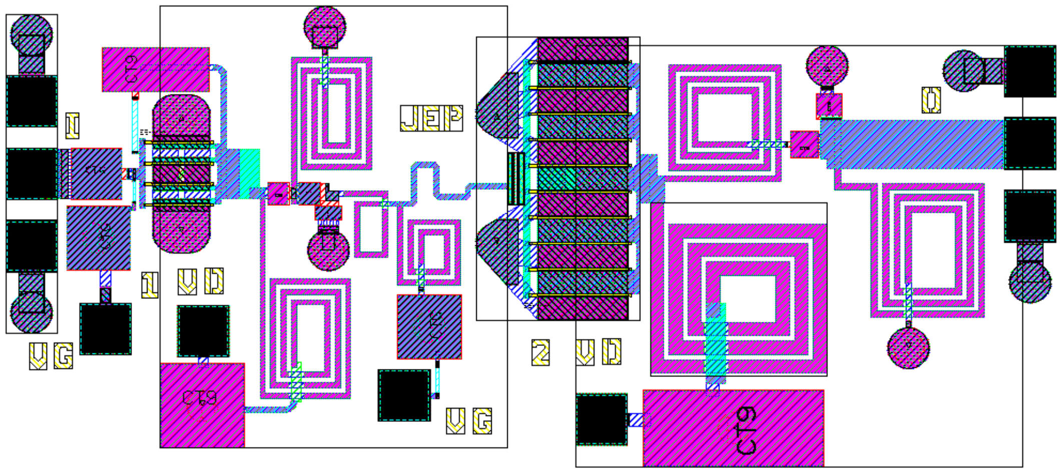

Fig. 9 **Final layout of 8- to 10-W Gen2 2-stage (3- to 7-GHz) 1.75-mm GaN HEMT PA (2.0 × 0.9 mm)**

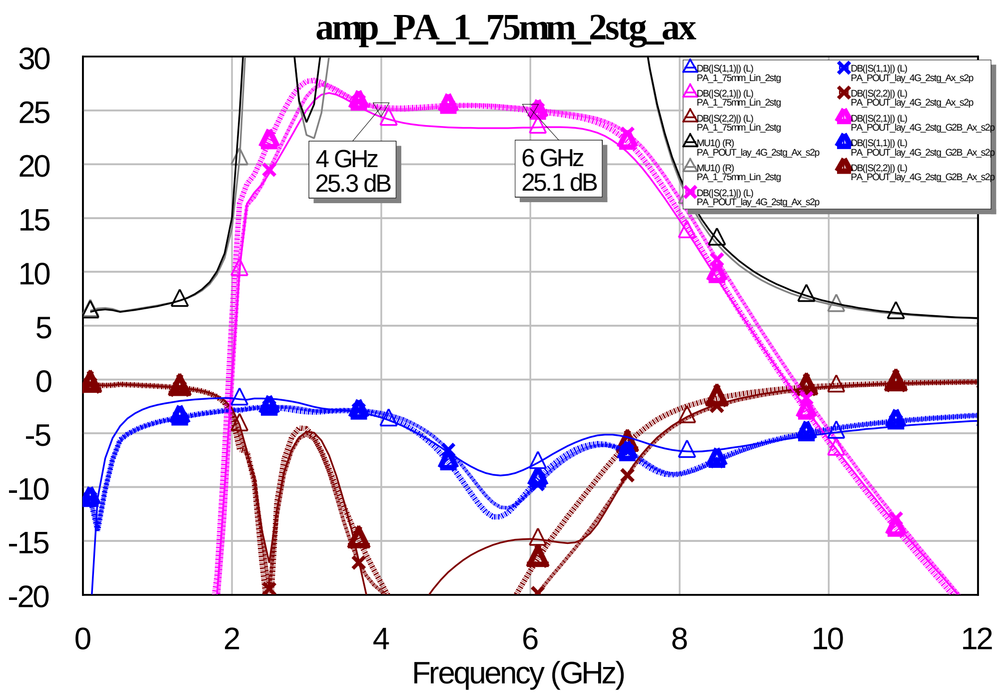

Fig. 10 **Simulations of 8- to 10-W 2-stage (3- to 7-GHz) 1.75-mm GaN HEMT PA (MWO, Axiem EM)**

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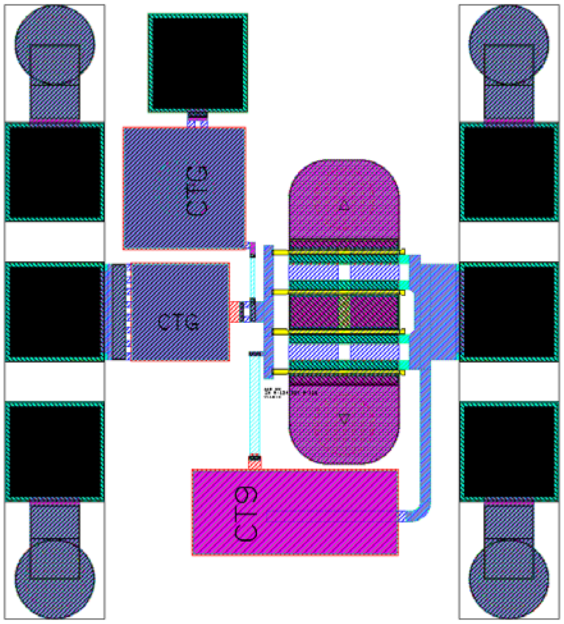

Fig. 11 Layout plot of a stand-alone broadband feedback amplifier (0.6 × 0.6 mm)

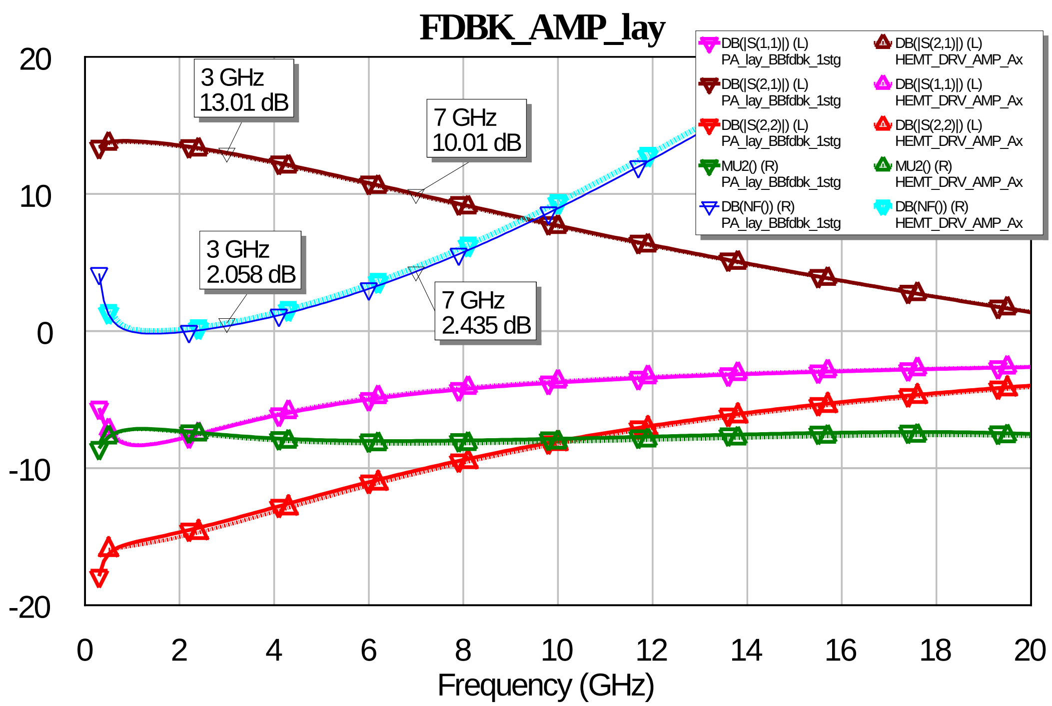

Fig. 12 Simulations of a stand-alone broadband feedback amplifier (MWO, Axiem EM)

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5. Voltage-Controlled Oscillator (VCO)

A high-frequency, integrated-voltage controlled oscillator design around 15 GHz was designed using the Qorvo 0.25-µm GaN process. A HEMT is used as a variable capacitor (e.g., Varactor) to tune the compact GaN VCO. While this compact design may not have the tuning range or low-phase noise required in certain applications, it does demonstrate the feasibility, tuning range, efficiency, and output power of an integrated GaN VCO. Plots of the GaN VCO layout and a simulation are shown in Figs. 13 and 14. This design should operate well over a DC voltage bias of 10 V, or less, up to 28 V, or higher. Varying the operating DC bias can help optimize the output power and efficiency of the VCO, though it is intended as a demonstration of capability and is not optimized for a particular output power, nor high efficiency.

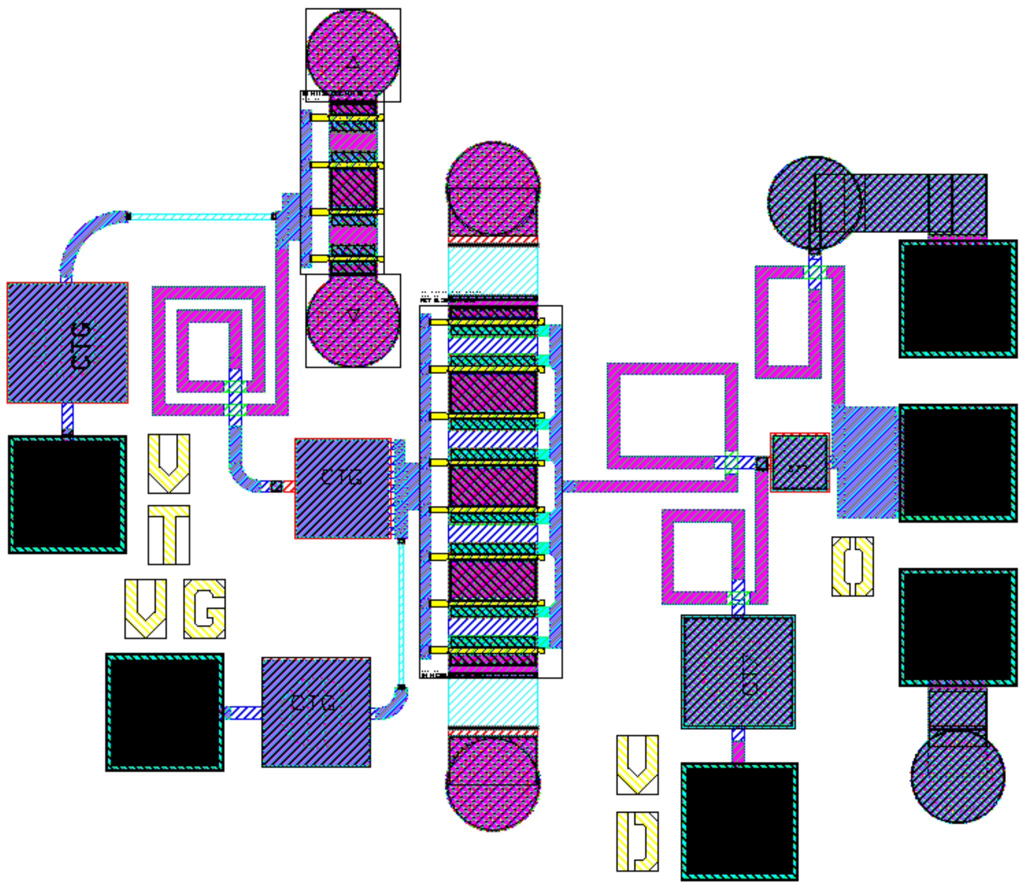

Fig. 13 Layout of a 15-GHz voltage-controlled oscillator (0.85 × 0.75 mm)

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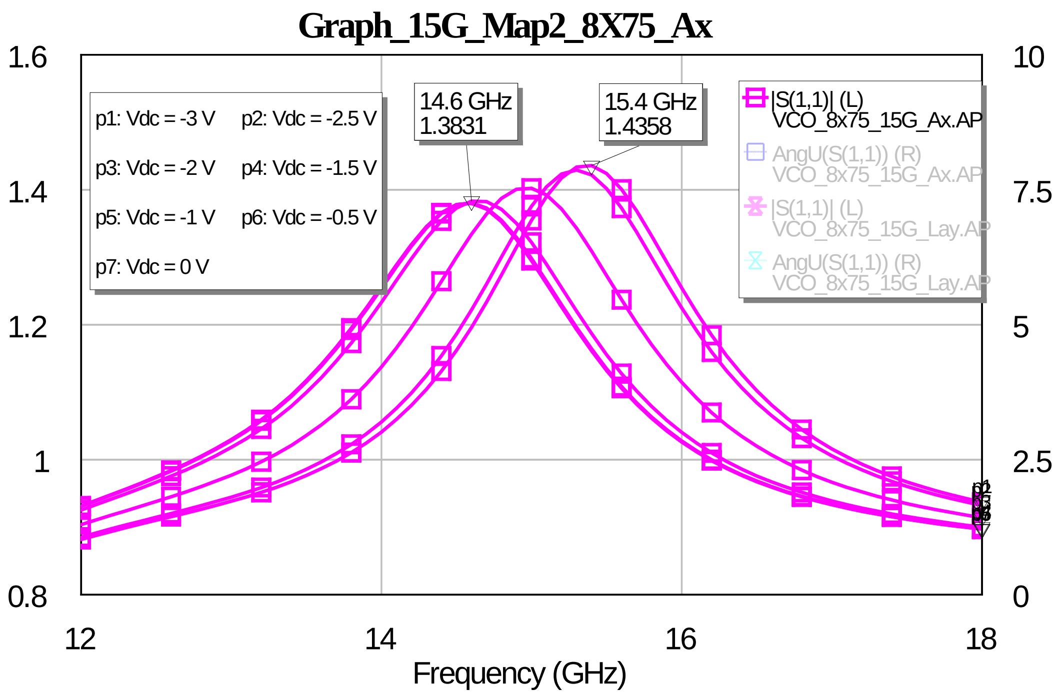

Fig. 14 Simulations of a 15-GHz voltage-controlled oscillator (Axiem EM)

6. Broadband Distributed Power Amplifier (GaN)

A very broadband distributed amplifier was designed in Qorvo's 0.25-µm GaN on SiC process. The simple design is not as efficient as a narrower band PA, such as the earlier designs, but it does have good output power and reasonable power efficiencies, which can be optimized by adjusting the DC operating conditions. This design is expected to operate well over a DC voltage bias of 10 V, or less, up to 28 V, or higher. Plots of the broadband distributed amplifier layout and simulation are shown in Figs. 15 and 16.

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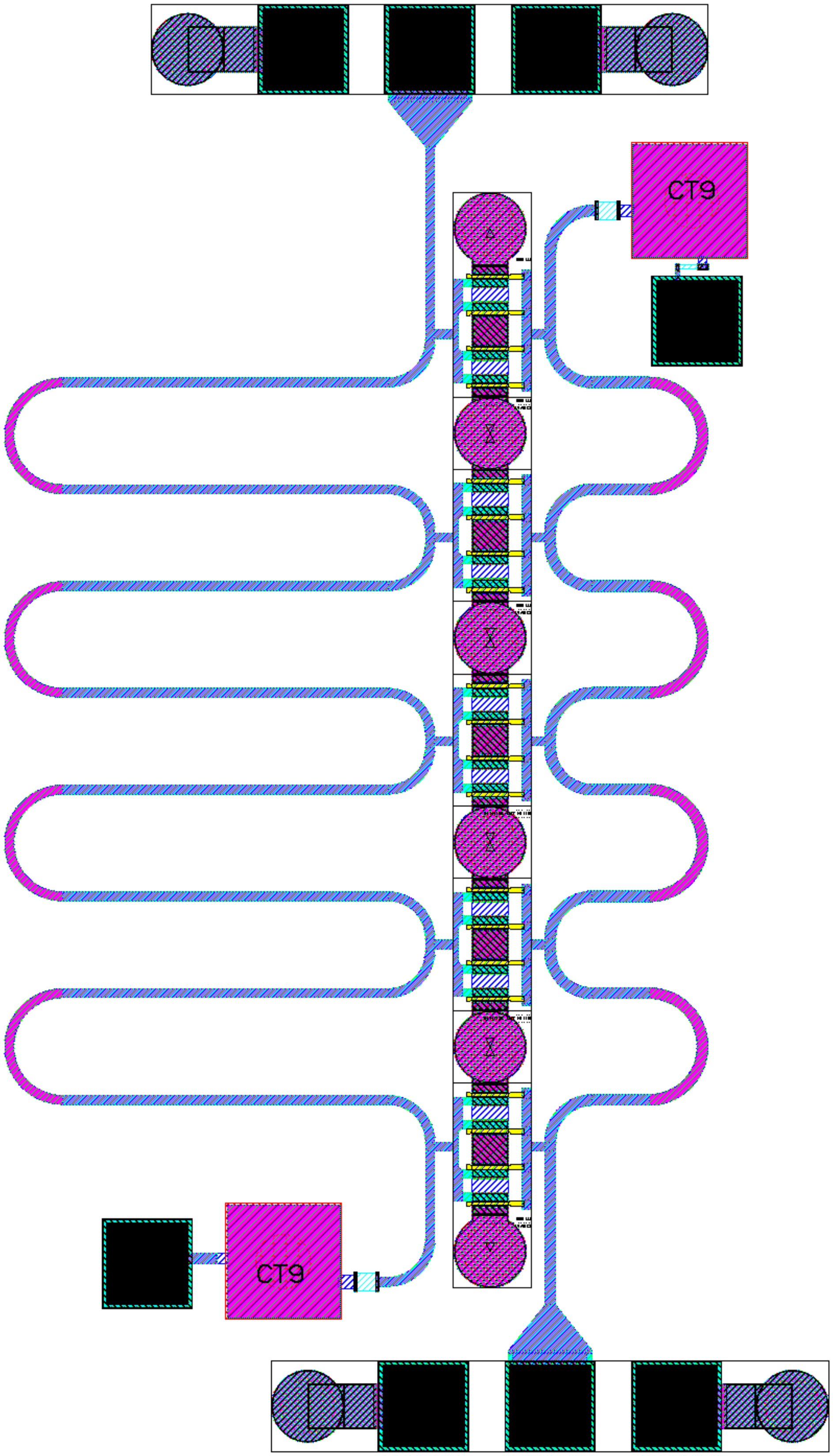

Fig. 15 Layout of a broadband distributed amplifier (1.6 × 0.75 mm)

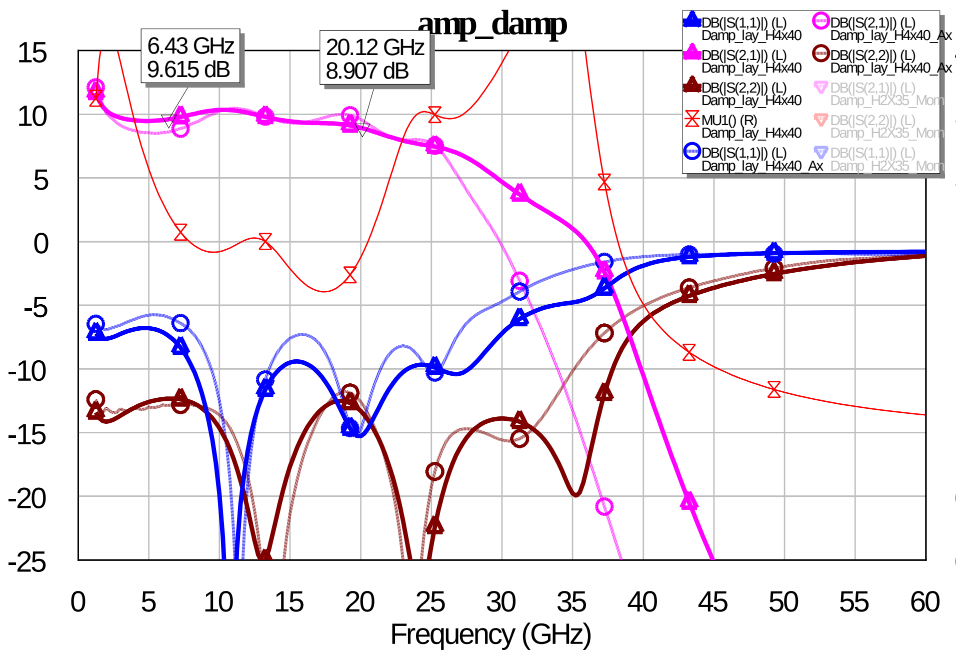

Fig. 16 Simulations of a broadband distributed amplifier (MWO, Axiem EM)

7. Summary and Conclusion

Several MMIC designs were submitted to an AFRL-sponsored Qorvo 0.25-µm GaN wafer fabrication to demonstrate the performance, bandwidth, capability, versatility, and applicability of GaN for compact, efficient, microwave circuit designs.

The strengths of GaN technology for high-power, very efficient PAs made the design of a broadband 3- to 7-GHz 8-W (28-V) 1.75-mm HEMT PA of particular interest. A driver amplifier stage was added to this design to create a two stage broadband high gain amplifier with relatively flat gain across the 3- to 7-GHz band of operation. Both the single-stage PA, 2-stage PA, and single-stage driver amplifier were submitted for fabrication. There may not be die space for all 3 of these designs, likewise for some of the other submitted designs mentioned in this report.

The distributed amplifier was particularly interesting for having extremely broad band gain above 20 GHz, with reasonable output power and efficiency. Varying the output DC bias can optimize the output power and efficiency of these 0.25-µm GaN HEMT designs, though 28 V is the nominal design target. The devices can handle higher DC voltages but were not optimally matched for higher operating voltages.

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Other designs include a TR switch that was designed for operation to 18 GHz. Using GaN HEMT switches increases the linear operating range of this design, though the HEMT switches had to be made small enough to operate to 18 GHz, with a sacrifice in higher insertion loss. Demonstrating the ability to integrate a voltage-controlled oscillator with GaN HEMTs as the varactor, and a GaN HEMT for the power stage, a 15-GHz VCO was submitted for fabrication. Again, this circuit may not have priority for the final fabrication due to space limitations.

Passive power combiner circuits with isolation resistors that can handle the high powers of GaN amplifiers are included in the fabrication. A simple 3- to 6-GHz single-stage passive Wilkinson coupler using a Mesa resistor for isolation will likely be included in the fabrication. Dana Sturzebecher of Qorvo, designed a 2-stage very broadband compact low-frequency Wilkinson coupler to 3 GHz. Layout, EM simulations, and design rule checking of these 2 passive combiners was performed by the author. A brief description of the GaN MMIC designs submitted by ARL, for an AFRL-sponsored Qorvo 0.25-µm GaN wafer fabrication are included in this technical report. Other technical reports will yield more detailed design information, and later, test and evaluation of the designs when the MMICs are available.

List of Symbols, Abbreviations, and Acronyms

AFRL	Air Force Research Laboratory
ARL	US Army Research Laboratory
DC	direct current
EM	electromagnetic
GaN	gallium nitride
HEMT	high-electron mobility transistor
MMIC	monolithic microwave integrated circuit
MWO	Microwave Office (computer-aided design tool)
PA	power amplifier
RF	radio frequency
SiC	silicon carbide
SPDT	Single-Pull Double-Throw
TR	transmit\receive
VCO	voltage-controlled oscillator

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