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US Army Research Laboratory

Gallium Nitride Monolithic Microwave Integrated Circuit Designs Using 0.25-µm Qorvo Process

by John E Penn

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14. ABSTRACT

The US Army Research Laboratory is exploring devices and circuits for radio frequency communications, networking, and sensor systems of interest to US Defense Department applications, particularly for next-generation radar systems. Broadband, efficient, high-power, monolithic microwave integrated circuit (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 technical note briefly summarizes a few of the MMIC 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
MMIC, GaN, amplifier, switch, coupler

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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 use to design broadband amplifiers, power amplifiers, and other circuits for future radar, communications, and sensor systems. Recently, several ARL designs were submitted for fabrication as part of an Air Force Research Laboratory (AFRL)–led effort. This technical report documents some of those monolithic microwave integrated circuit (MMIC) designs to demonstrate the performance, bandwidth, capability, versatility, and applicability of GaN for compact, efficient, MMIC designs. A separate report documents the broadband power amplifier that was part of this same effort.[1]

2. High-Power Couplers (GaN)

A lumped-element passive Wilkinson coupler for combining high-power amplifier stages was designed in Qorvo’s 0.25-µm GaN-on-silicon-carbide (SiC) process. One concern for power limits in a passive combiner is the isolation resistor. For this 3- to 6-GHz coupler design, a 250-µm-wide mesa resistor was used for the 100-ohm isolation resistor. Since GaN-on-SiC is an excellent thermal conductor, the isolation resistor should be able to handle a significant amount of power. It may be hard to test the limits of this design, especially on a probe station. Test cells of various smaller resistor types might provide a better comparison of a mesa resistor versus a thin-film resistor. Mesa-resistor temperature rise is expected to be minimal and should handle significantly more power than a thin-film resistor. One downside is that there may be more process variation in mesa resistors than in thin-film resistors.

The typical distributed 3-port Wilkinson coupler consists of 2 transmission lines, with a characteristic impedance of 70.7 ohm and an electrical length of 90° at the design frequency plus a 100-ohm isolation resistor between the 2 equal power split ports. For a lumped-element implementation, the transmission lines are replaced by series and shunt capacitors. A schematic of the lumped-element Wilkinson coupler is shown in Fig. 1. Figure 2 shows the layout of a lumped-element Wilkinson coupler with the common port on the right leading to 2 lumped-element-equivalent transmission lines of shunt capacitor, series inductor (spiral inductor), and shunt capacitor, to a mesa resistor in order to provide isolation between the top and bottom split power ports. Analytical and Axiem electromagnetic (EM) simulations of the coupler are shown in Fig. 3, exhibiting better than a 10-dB return loss and about 0.5 dB of additional loss (over ideal) from 3 to 6 GHz. The size of the resistor is a compromise width of 250 µm. A larger size would increase power handling capacity in the isolating resistor, while a smaller size would allow for higher-frequency performance.

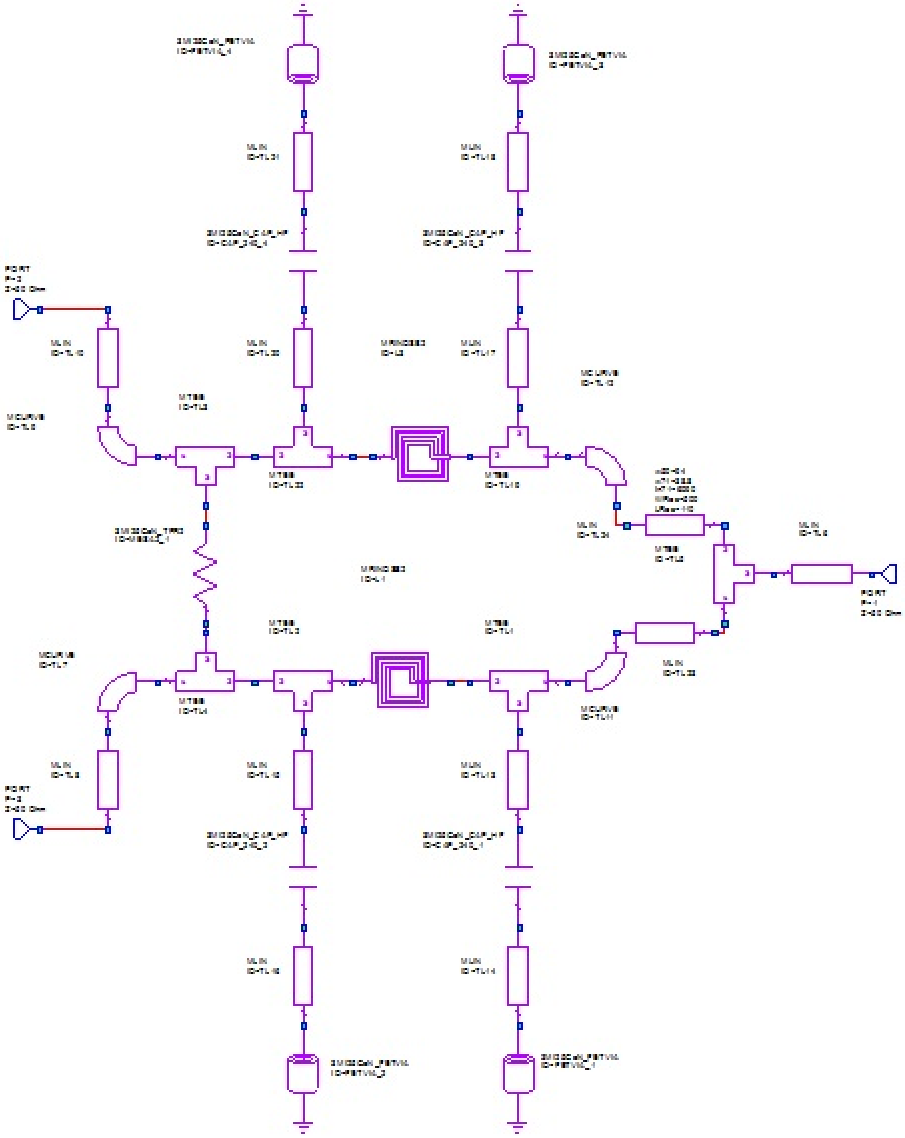

Fig. 1 Schematic of 3- to 6-GHz lumped-element Wilkinson coupler

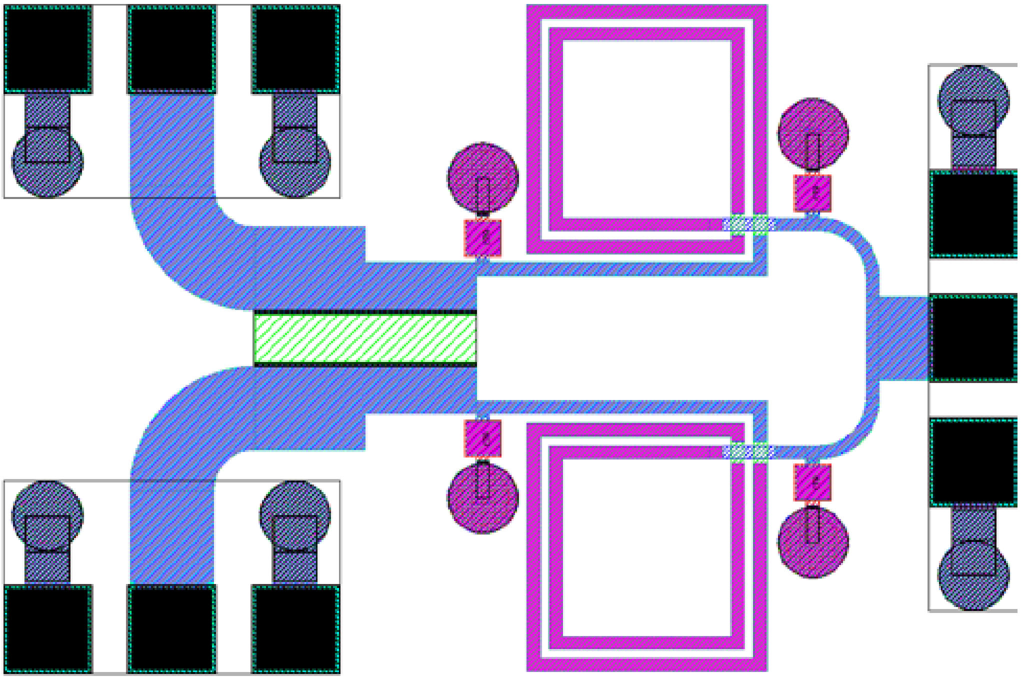

Fig. 2 Final layout of 3- to 6 GHz-Wilkinson coupler Gen2 GaN (1.15 × 0.75 mm)

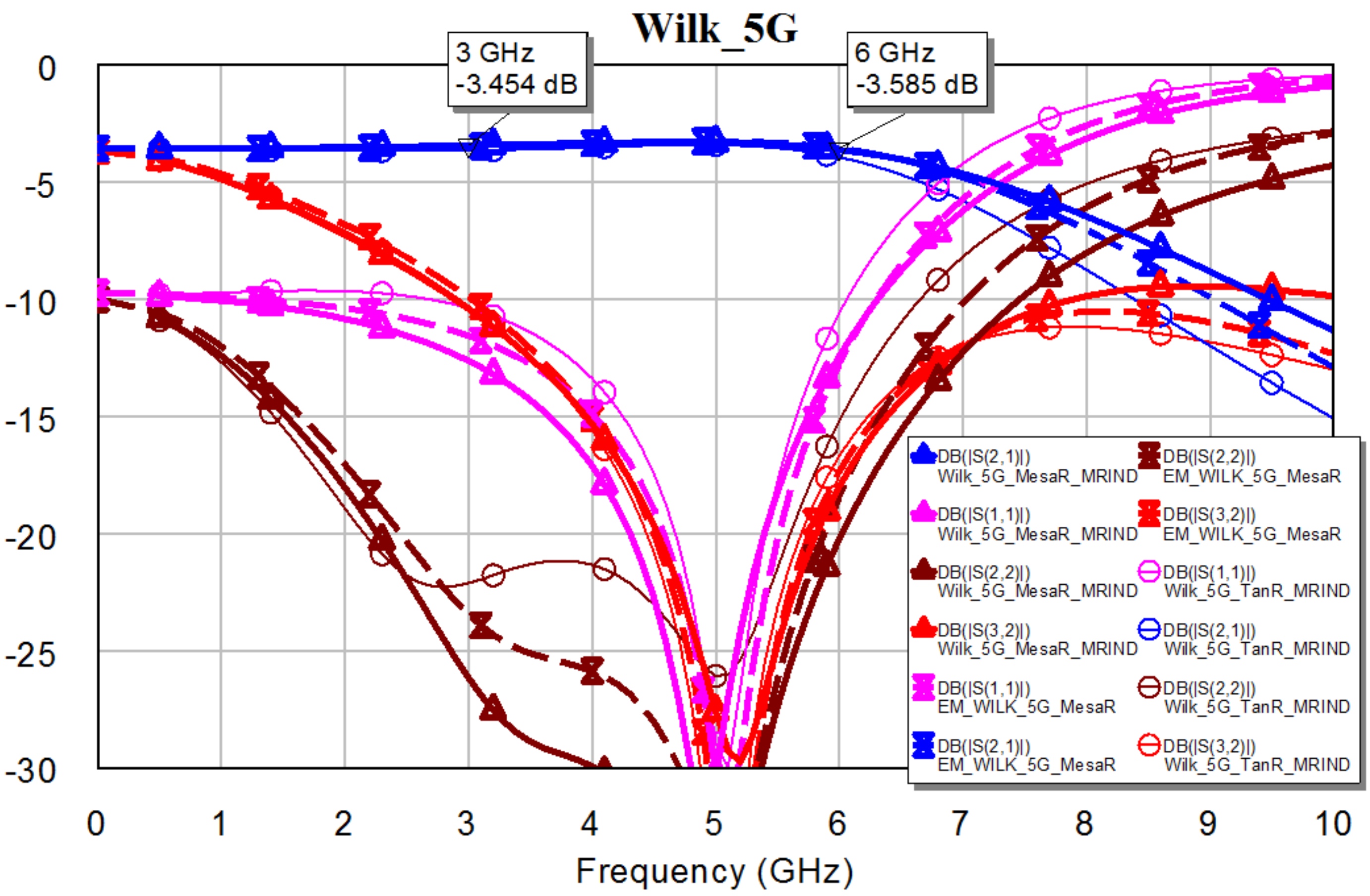

Fig. 3 Simulations of 3- to 6-GHz Wilkinson coupler Gen2 GaN (Microwave Office [MWO], Axiem EM)

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

A simple GaN high-electron-mobility-transistor (HEMT) TR single-pull double-throw (SPDT) switch consists of at least 2 series- and 2 shunt-arranged HEMTs configured and DC–biased such that the common path, typically the antenna, is connected through series HEMT to a desired input or output port and isolated from the other input/output port with a shunt HEMT. Bandwidth, insertion loss, and power handling capability are determined by the size of the series and shunt HEMTs and the quality of the process for switches, with the switch figure of merit expressed as a resistance-times-capacitance (RC) product. Increasing the size of the HEMT switch proportionally reduces the series resistance in the On state as desired but increases the shunt capacitance in the Off state, which is not desired. There are narrow-band ways to increase performance by offsetting the Off state capacitance with series or shunt inductors, but it is difficult to absorb the series and shunt capacitances for a broadband operation exceeding a decade. A simple TR switch that works well up to 6 GHz is shown in Figs. 4 (layout) and 5 (simulation). Complementary DC-bias voltages are applied at inputs A and B, typically 0 V for On, and less than –6 V for Off. When A is On, the series switch connects port 1 to port 3 at the bottom, then connects the shunt switch to isolate port 2 at the top, and while B is Off, turning off the shunt switch at port 3 and turning off the series switch from port 1 to port 2 at the top. Reversing the DC biases at A and B would connect port 1 to port 2 at the top while isolating port 3 at the bottom. At 4 GHz, the insertion loss is predicted as 1.3 dB, with a return loss of better than 13 dB and an isolation greater than 34 dB.

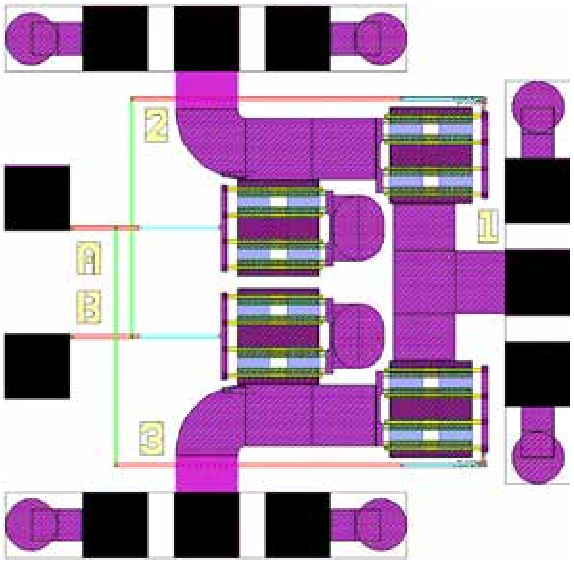

Fig. 4 Layout of broadband DC-6-GHz SPDT TR switch 0.25-µm GaN (1 × 1 mm)

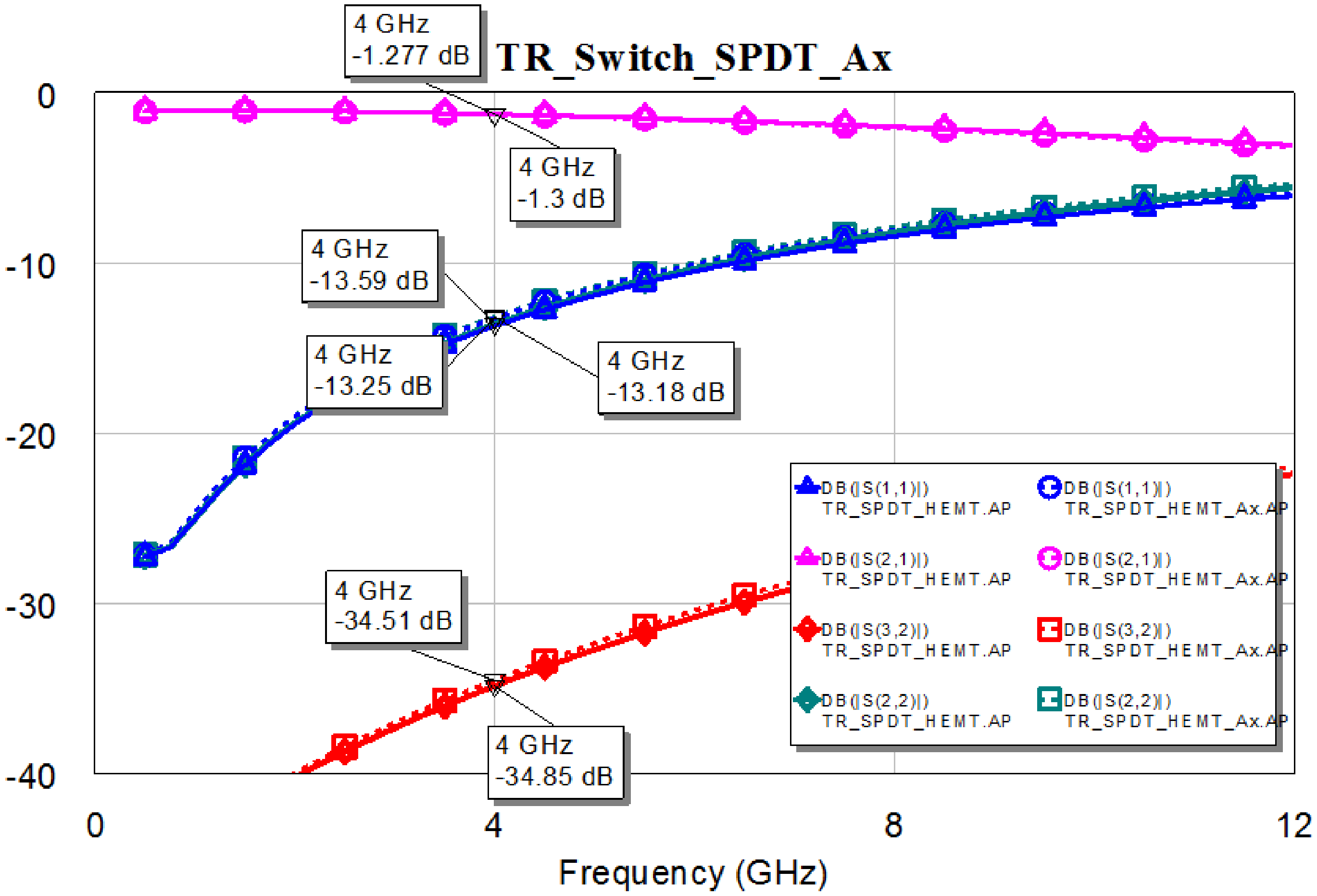

Fig. 5 Simulation of broadband DC-6-GHz SPDT TR switch 0.25-µm GaN (MWO, Axiem EM)

To achieve a broadband TR SPDT switch designed to operate from near DC up to 18 GHz using Qorvo’s 0.25-µm GaN-on-SiC process, the HEMTs had to be made smaller to achieve performance at the high end of the band. The tradeoff in size, topology, and performance resulted in higher insertion loss than desired to achieve broadband performance up to 18 GHz. While the earlier TR switch design had lower insertion loss, it only operated up to about 6 GHz before the return loss fell below 10 dB. Figures 6–8 show the schematic, layout, and simulations, respectively, of a broadband 0.1- to 18-GHz TR switch (SPDT). There are 2-shunt HEMTs in each path rather than a single-shunt switch to improve the high-end performance. Likewise, the DC bias voltage inputs at A and B are complementary, switching the common port to one or the other of the top or bottom ports (the port numbers are renumbered vs. the previous example). In the simulation, insertion loss is a moderate 1.5 dB below 7 GHz, increasing to 2 dB at 14 GHz, then increasing to 2.5 dB at the 18-GHz band edge. There are thin-film resistors to isolate the DC switch biases on the HEMT gates from the source and drain radio-frequency switch connections. This may limit (RC delay) how quickly the TR switch can be transitioned from receive to transmit.

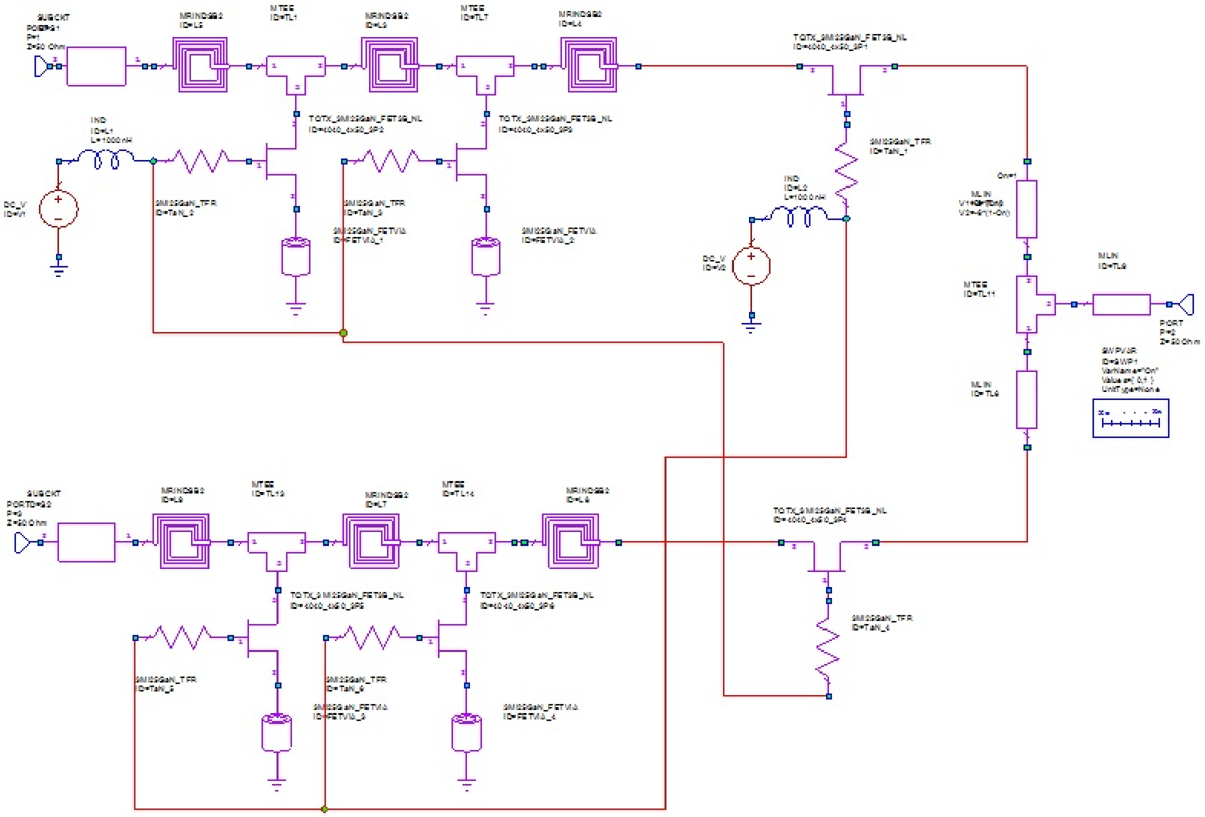

Fig. 6 Schematic of broadband 0.3- to 18-GHz SPDT TR switch 0.25-µm GaN HEMTs

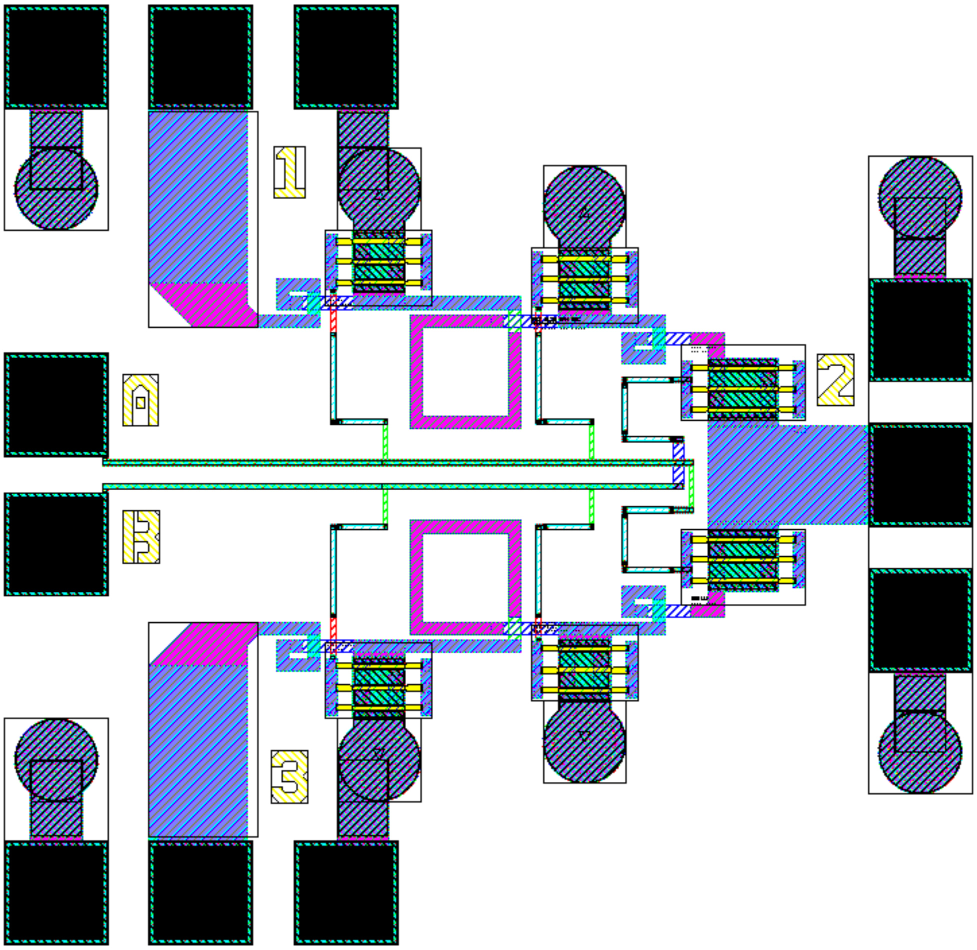

Fig. 7 Final layout of broadband 0.3- to 18-GHz SPDT TR switch Gen2 GaN (0.9 × 0.9 mm)

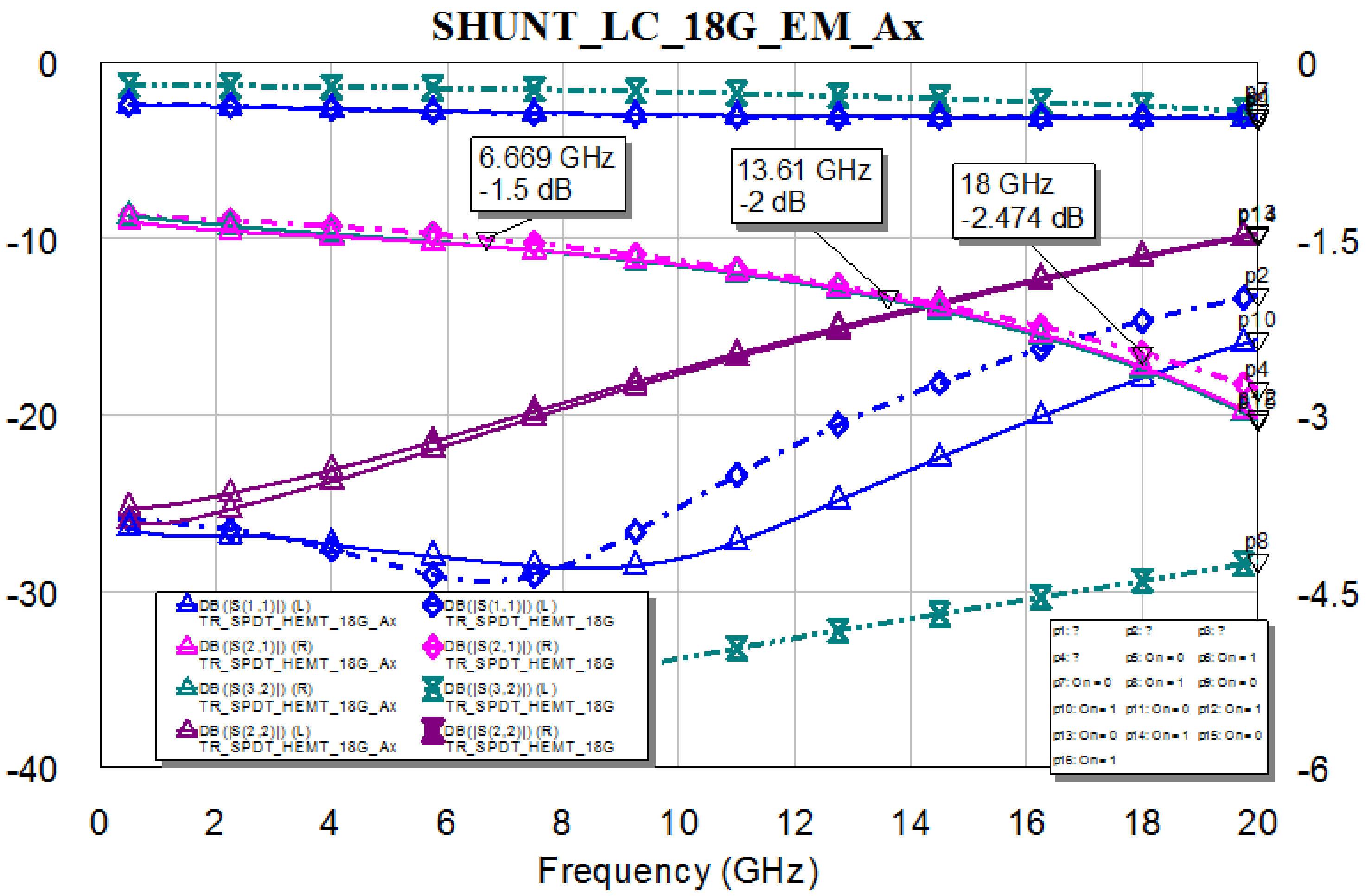

Fig. 8 Simulations of broadband 0.3- to 18-GHz SPDT TR switch Gen2 GaN (0.9 × 0.9 mm)

4. 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 amplifier optimized for power but 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 and up to 28 V or higher. Plots of the broadband-distributed-amplifier schematic, layout, and small-signal simulation are shown in Figs. 9–11, respectively. Power performance at 8, 10, 15, and 20 V with output power but decreasing power-added efficiencies (PAEs) are shown in Figs. 12–15, respectively. PAEs are reasonable at 20%–25% at the lower 8-V drain bias but decrease at higher DC voltages. Output power is about 1/2 W with 10-V drain bias and over 1 W when the drain bias is increased to 20 V.

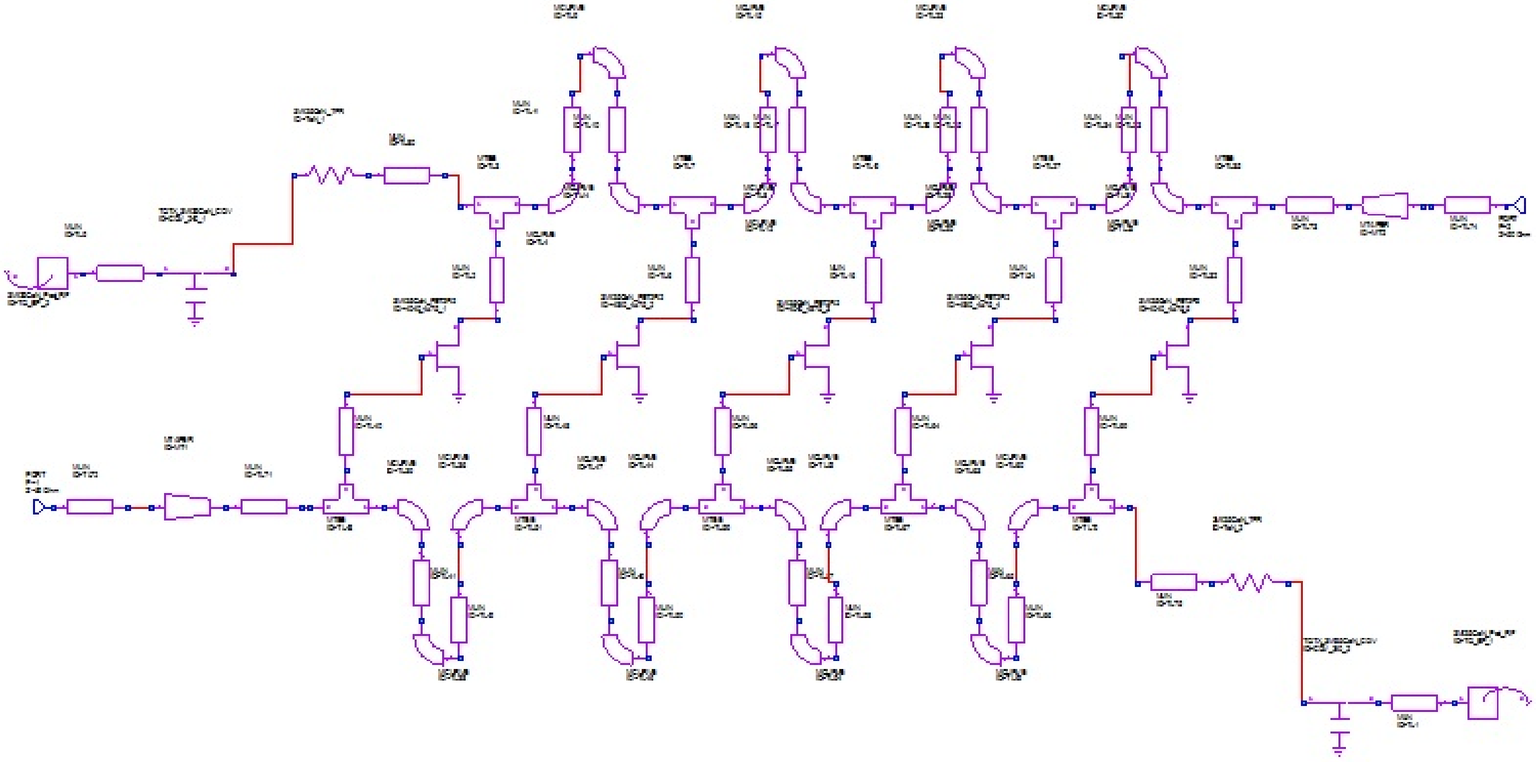

Fig. 9 MWO schematic of broadband-distributed amplifier

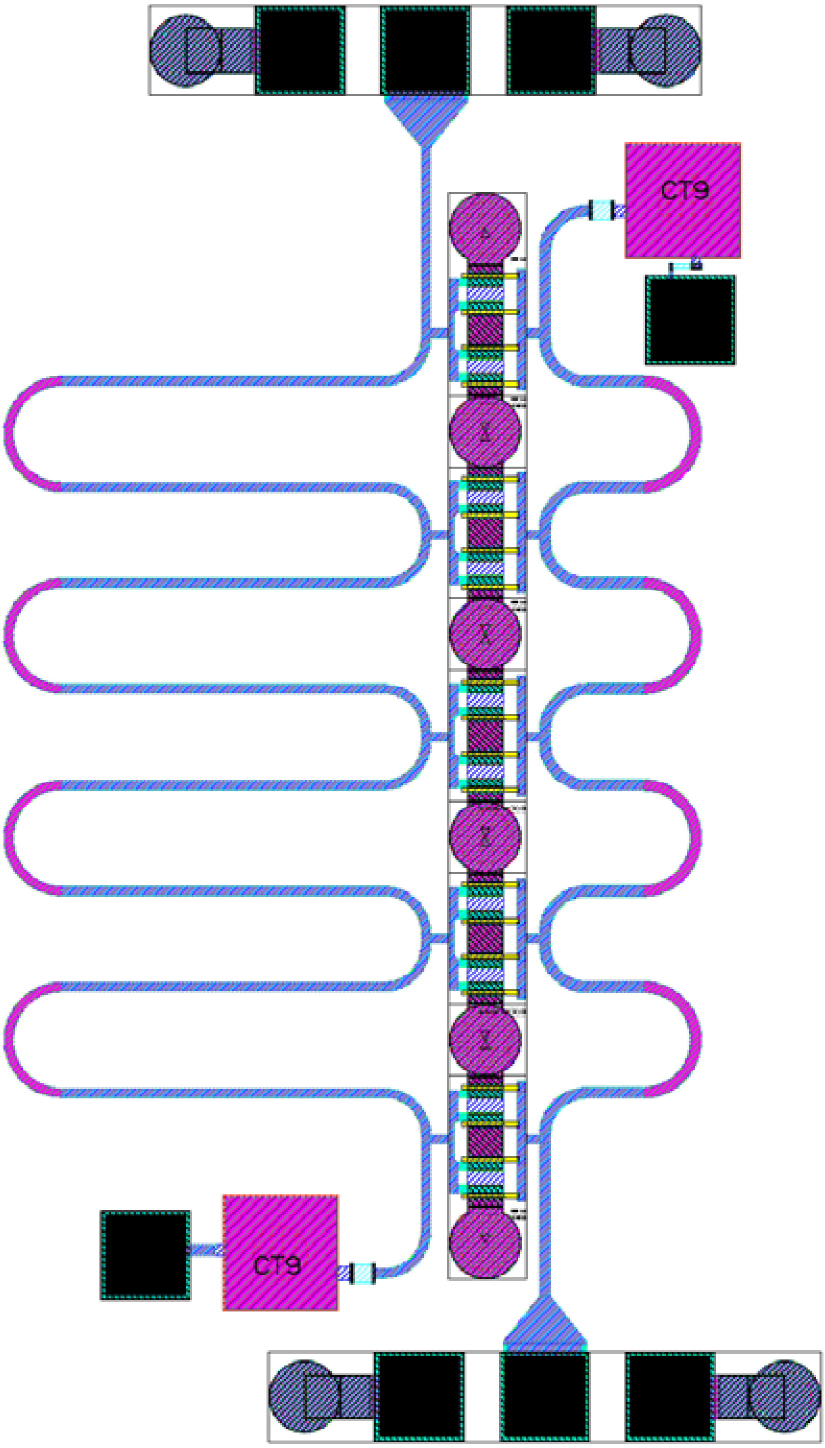

Fig. 10 Layout of broadband-distributed amplifier (1.6 × 0.75 mm)

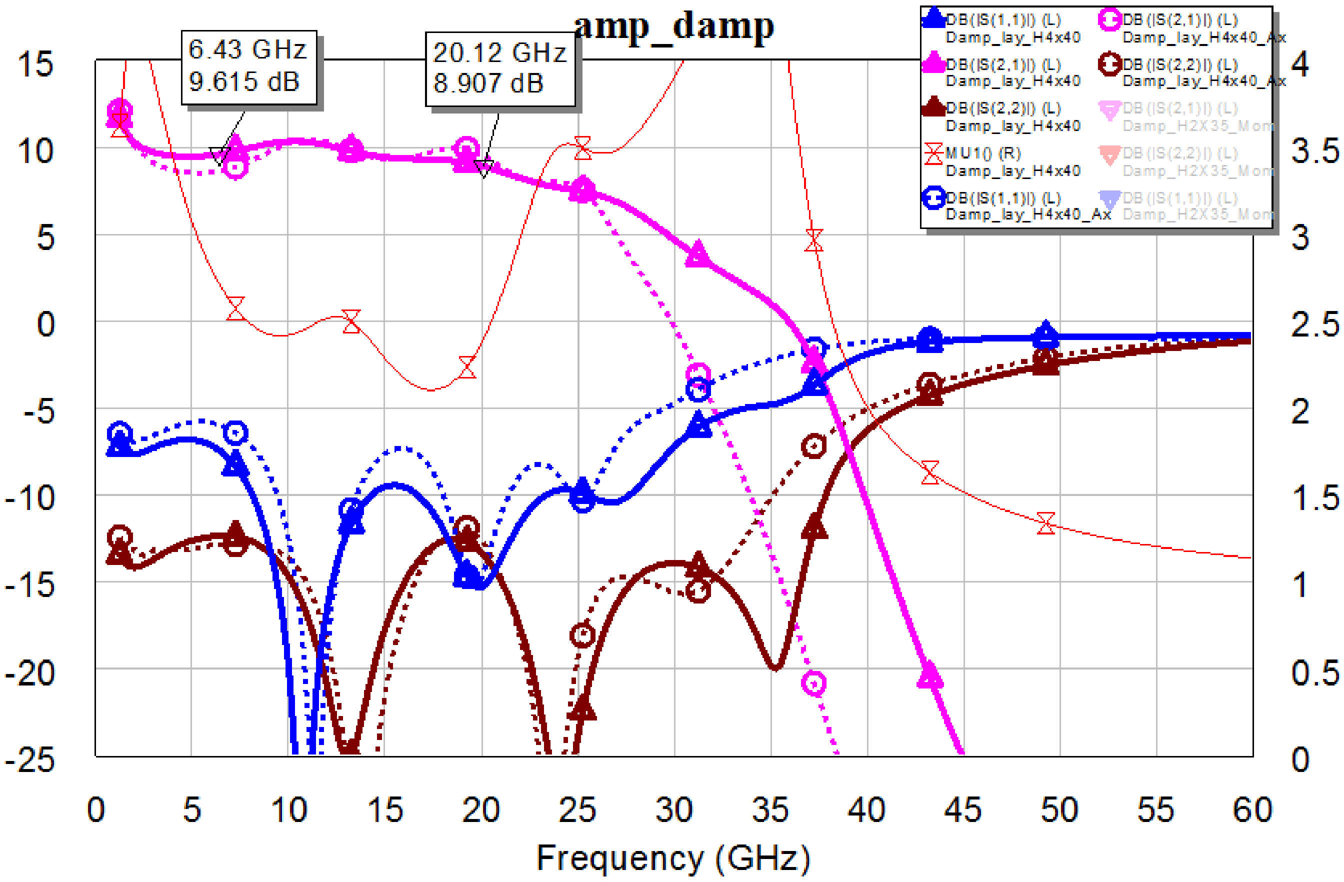

Fig. 11 Simulations of broadband-distributed amplifier (MWO, Axiem EM)

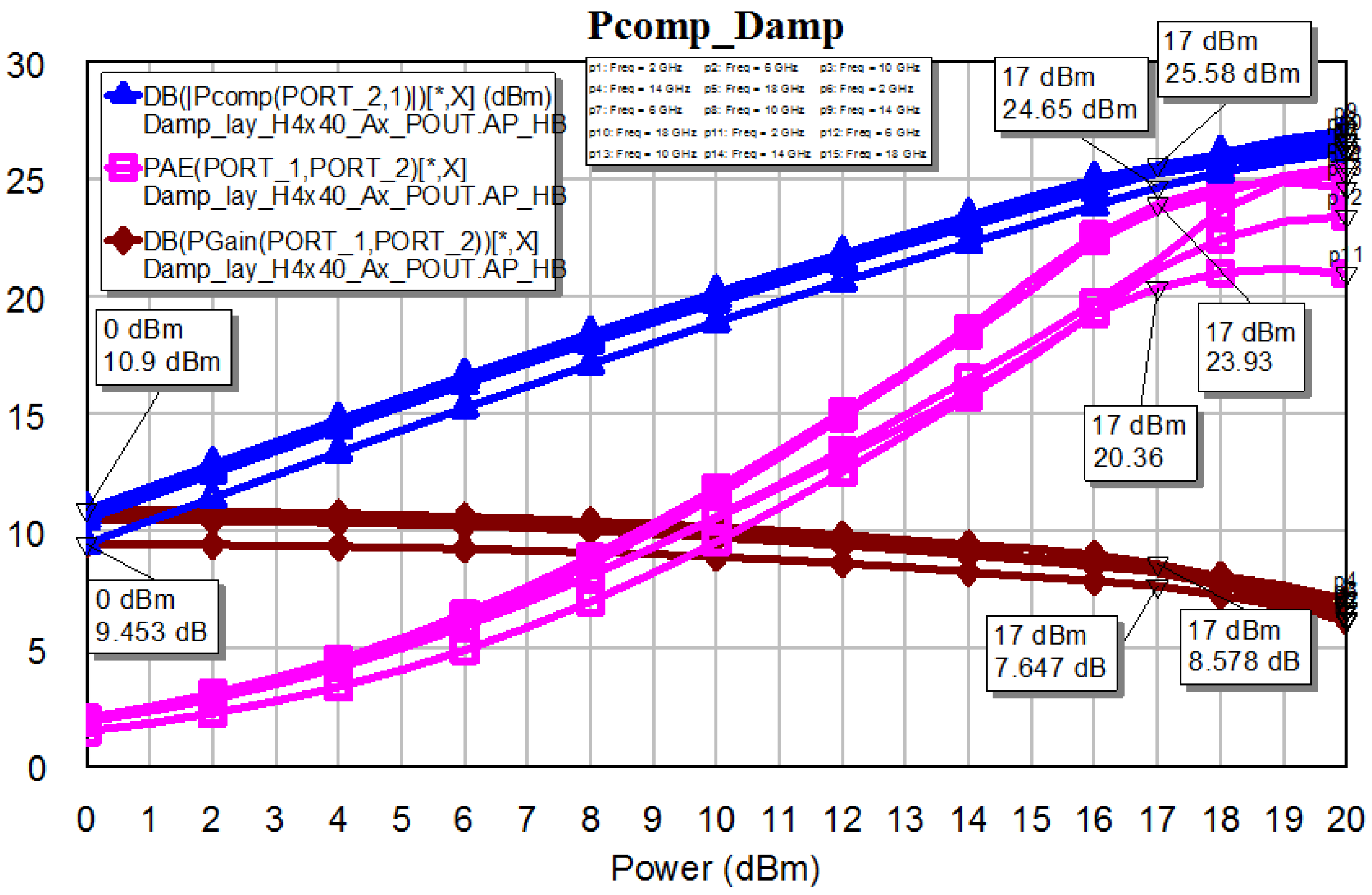

Fig. 12 Power performance simulations of broadband-distributed amplifier 2–18 GHz (DC: 8 V, 66 mA)

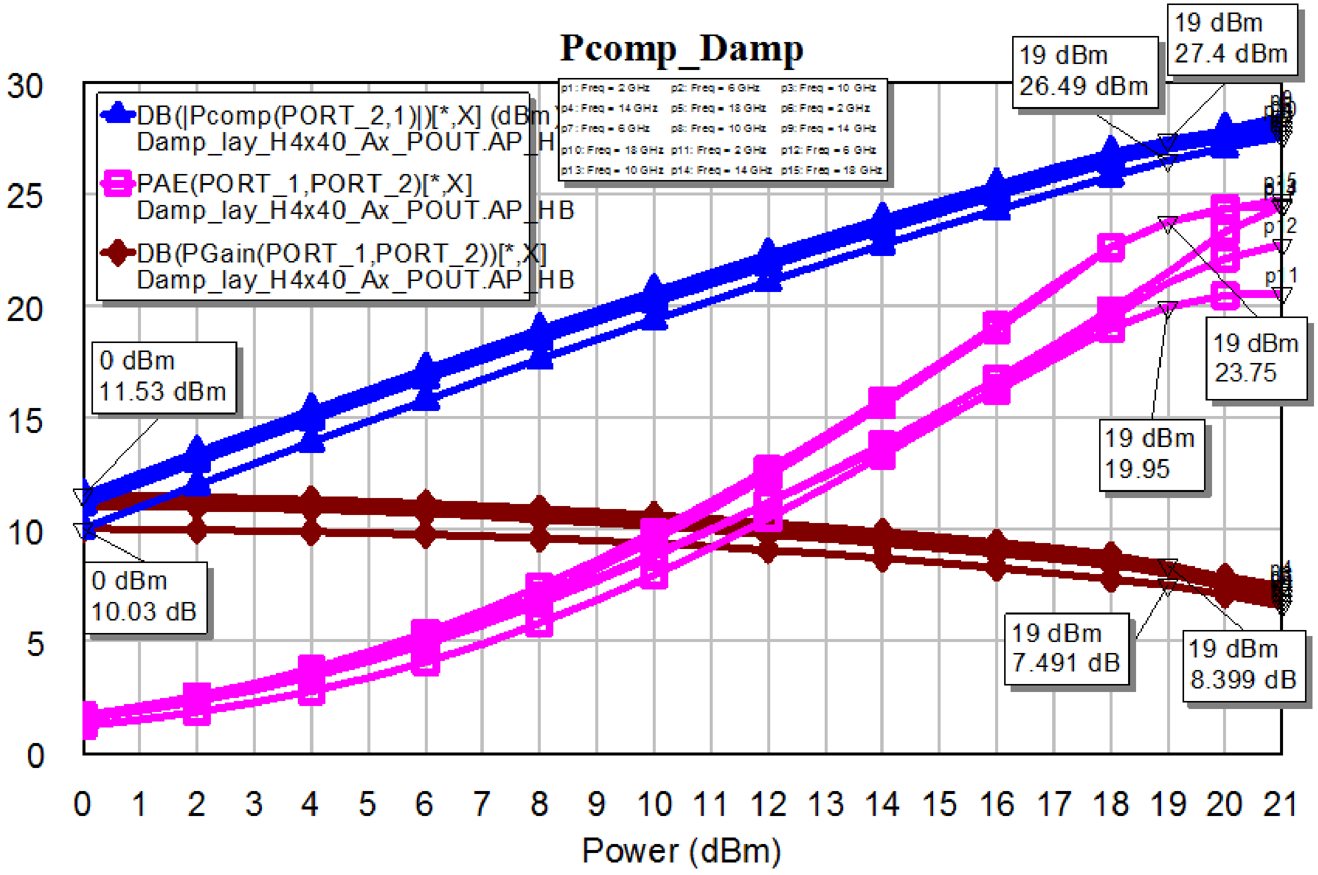

Fig. 13 Power performance simulations of broadband-distributed amplifier 2–18 GHz (DC: 10 V, 75 mA)

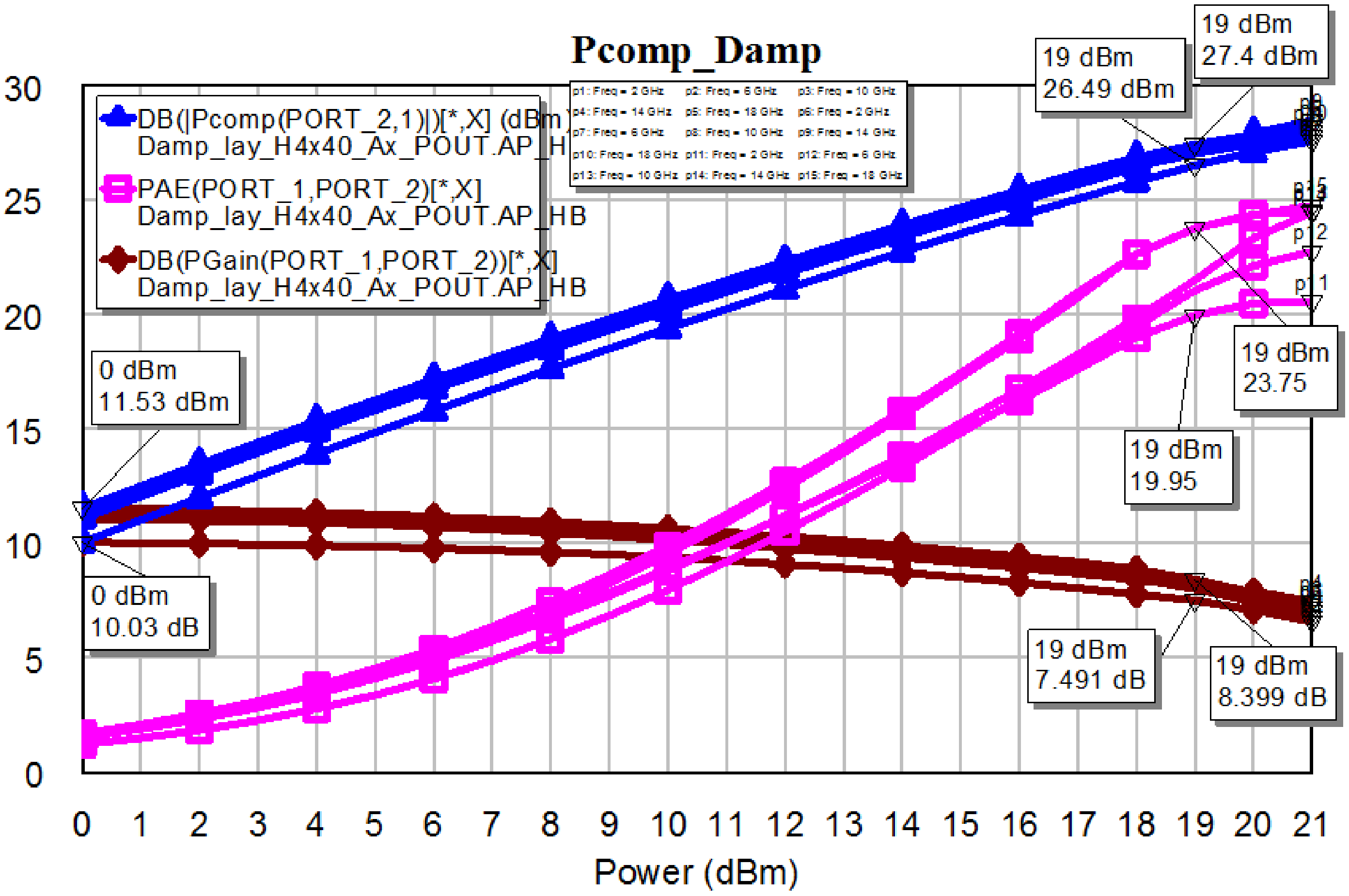

Fig. 14 **Power performance simulations of broadband-distributed amplifier 2–18 GHz (DC: 15 V, 94 mA)**

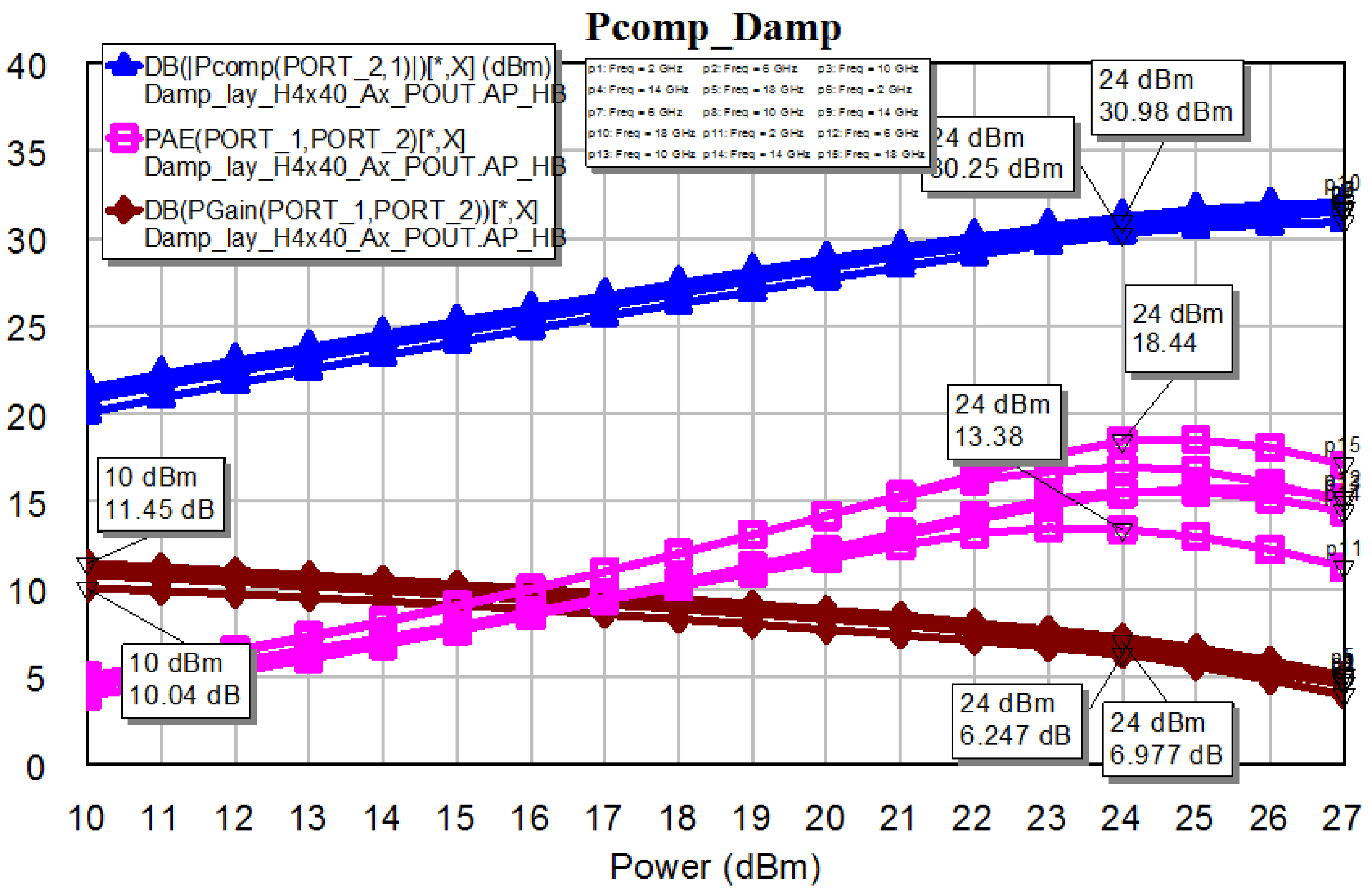

Fig. 15 Power performance simulations of broadband-distributed amplifier 2–18 GHz (DC: 20 V, 106 mA)

5. Summary and Conclusions

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 and efficient microwave circuit designs.

The distributed amplifier was particularly interesting for having extreme broadband 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 desired. The 0.25-µm HEMTs can handle higher DC voltages but were not optimally matched for higher operating voltages. For this design, PAEs are higher at lower DC bias voltages such as 8 or 10 V.

Other designs include a TR switch that was designed for operation to 18 GHz. Using GaN HEMT switches increases the linear operating range of TR switches over previous gallium arsenide designs. The need to reduce the HEMT switch sizes to increase operation to 18 GHz will sacrifice power handling capability and increase insertion loss.

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. Layout, EM simulations, and design rule checking of these designs were performed by the author. A brief description of all the GaN MMIC designs submitted by ARL for an AFRL-sponsored Qorvo 0.25-µm GaN wafer fabrication are included in another technical note.[2] Later technical reports will detail design tests and evaluations when the MMICs are available.

6. References

1. Penn JE. Broadband 0.25-µm gallium nitride (GaN) power amplifier designs. Aberdeen Proving Ground (MD): Army Research Laboratory (US); to be published 2017.

2. Penn JE. Gallium nitride (GaN) monolithic microwave integrated circuit (MMIC) designs submitted to Air Force Research Laboratory (AFRL)-sponsored Qorvo fabrication. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2017 July. Report No.: ARL-TN-0835.

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 (CAD tool)
PAE	power-added efficiency
RC	resistance times capacitance
SiC	silicon carbide
SPDT	single-pull double-throw
TR	transmit/receive

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