NASA/TM—2019-220359

Multi-Band and Multi-Function Reconfigurable Gallium Nitride Based Fully Solid-State Microwave Power Module for Cognitive Radio/Radar Platforms

Rainee N. Simons and Seth W. Waldstein
Glenn Research Center, Cleveland, Ohio

November 2019

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2019-220359

Multi-Band and Multi-Function Reconfigurable Gallium Nitride Based Fully Solid-State Microwave Power Module for Cognitive Radio/Radar Platforms

Rainee N. Simons and Seth W. Waldstein
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2019

Acknowledgments

The authors would like to thank the SCaN Project Office for thier support. Additionally, the authors would like to thank the Center Innovation Fund for the support. The figures for this NASA TM are archieved under E-19749.

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Multi-Band and Multi-Function Reconfigurable Gallium Nitride Based Fully Solid-State Microwave Power Module for Cognitive Radio/Radar Platforms

Rainee N. Simons and Seth W. Waldstein
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

This paper presents as a proof-of-concept (POC) the design, integration, and performance of a novel reconfigurable S-/X-band Gallium Nitride (GaN) based fully solid-state microwave power module (SSMPM) for the role as the transmit module in a cognitive radio (CR). The SSMPM synergistically integrates multiple amplifiers through diplexing and high power switches to enable a single SSMPM capable of functioning as both S-/X-band amplifiers for telemetry, tracking, and command (TT&C), telecommunications, and science data downlink or as X-band radar for proximity sensing onboard a planetary exploration spacecraft. Integration of an electric field shaping field plate (FP) onto the GaN high electron mobility transistors (HEMTs) in this SSMPM provides increased performance and reliability for operation in the harsh conditions of space. This SSMPM is capable of delivering saturated power (P_{sat}) of 39 dBm (8 W continuous wave (CW)) at S-band, P_{sat} of 43 dBm (20 W CW) at X-band, and P_{sat} of >50 dBm (>100 W Pulsed) at X-band.

1.0 Introduction

Electromagnetic spectrum overcrowding and the inclusion of secondary users in frequency bands previously allocated for use by the National Aeronautics and Space Administration (NASA) has necessitated the development of reconfigurable communications modules. The artificial intelligence (AI) managed radio network is one viable approach for solving the problem of interference due to overcrowding of the spectrum (Ref. 1). Cognitive radios (CR) are AI based intelligent wireless communication system that exploits internal parameter tuning capability and knowledge of the external environment to enhance machine learning; and establish reliable communications through the efficient utilization of the radio spectrum. The transmitter portion of a CR is required to perform transmit-power control and dynamic spectrum management to tap into available channel bandwidth acquired from radio-scene analysis performed on the surrounding environment (Refs. 2 and 3).

NASA's Near-Earth Network (NEN) and Deep Space Network (DSN) supports satellites and interplanetary spacecraft missions through telemetry, commanding, ground-based tracking, and data/communications services at the NASA designated frequencies of S-band, X-band, and Ka-band. A typical payload on an Earth and planetary exploration spacecraft employs two separate S-band and X-band amplifiers for TT&C and science instruments and telecommunications. It is advantageous to develop a single wideband, reconfigurable high-power, high-efficiency unit that can operate at multiple frequency bands depending on the cognitive need at any given time. Proximity sensing of the surrounding environment using high power radar can further extend the knowledge base of the cognitive processor and prevent interference with neighboring conducting surfaces. Additionally, a single dynamically reconfigurable amplifier when integrated with reconfigurable antennas enables miniaturization of the overall RF system.

Historically, the term microwave power module (MPM) is associated with a small fully integrated self-contained radio frequency (RF) amplifier that combines both solid-state and microwave vacuum electronics technologies (Ref. 4). This paper present the research and development of a novel fully solid-state MPM, which is distinctly different from the above MPMs (Ref. 5).

In this paper, we present as a POC the design, integration, and performance of a novel reconfigurable GaN based fully solid-state MPM for use as the transmitter in a CR. The module synergistically integrates diplexers, pre-amplifiers, multistage medium power amplifiers (MPAs), single pole double through (SPDT) switches, and CW/Pulsed high power amplifiers (HPAs) with a voltage sequencer, a direct current (DC) blanking controller, and a low voltage electronic power conditioner (EPC). This SSMPM utilizes radiation hardened GaN transistors with advanced FP structures to increase device reliability and performance. The POC SSMPM operates at both S-band and X-band to serve multiple roles. The SSMPM can be reconfigured to deliver P_{sat} of 39 dBm (8 W CW) at S-band, P_{sat} of 43 dBm (20 W CW) at X-band, and P_{sat} of >50 dBm (>100 W Pulsed) at X-band.

2.0 Efficiency and Reliability

Efficiency of the power amplifier is an essential aspect of a spacecraft as it can consume 80 to 90 percent of the available power bus (Refs. 6 and 7). An increase in efficiency can result in lowered heat sink mass, an increase in device lifetimes and an increase in available power for science instruments. Novel circuit design topologies such as the class-F or class-E switching amplifies, cascode circuit arrangements, feed-forward linearization, or envelope tracking can all increase efficiency with varying tradeoffs in linearity, size and complexity.

Reliability is the paramount concern for all NASA space hardware. GaN HEMTs are uniquely conditioned to resist radiation-induced displacement damage due to the formation of a 2-D electron gas layer which re-injects scattered carriers; resulting in GaN HEMTs being 10 times more radiation tolerant than GaAs field effect transistors (FETs) (Ref. 8).

2.1 Field Plate

FP structure integrated onto the GaN HEMT gate, shown in the schematic of Figure 1, modulates the electric field locally to reduce the peak electric field along the transistor channel (Ref. 9), and increase the devices breakdown voltage (V_{BR}).

The increase in V_{BR} results in higher operating drain bias with a corresponding increase in power, linearity and reliability performance. The FP-induced depletion region decreases the current by suppressing the transport carriers from the surface, increasing the transportation path and distributes the electric field to reduce the peak field around the transistors contacts. This lessens the breakdown mechanism of tunneling and induced leakage currents from the gate terminal to the channel layer (Ref. 10).

The draw back with the addition of a FP can be a decrease in the transistors maximum oscillation cut-off frequency (f_{max}) due to an increase in gate-to-drain capacitance (C_{GD}).

A FP can be arranged on either the gate, drain or source contact of a transistor with the geometry determining the effect on reshaping of the electric fields. The effect of the geometric variations of various FP and insulator layer on the electric field distribution and corresponding V_{BR} has been thoroughly investigated in Reference 11.

3.0 Solid-State Microwave Power Module

3.1 Module Design and Mode of Operation

The SSMPM layout is schematically illustrated in Figure 2 and discussed previously in Reference 12. Through the use of diplexing and high-power switching this SSMPM provides the frequency reconfigurability required to switch between S-/X-band communications and X-band radar.

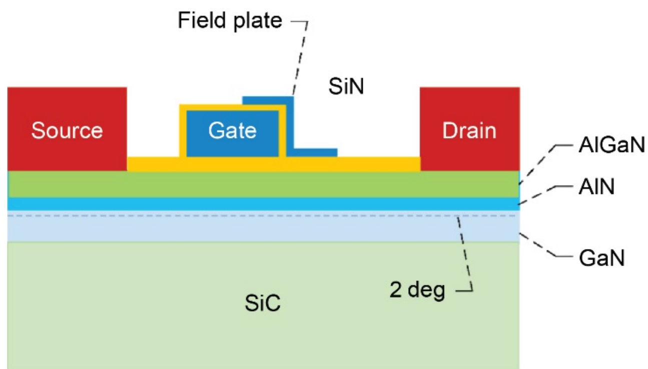

Figure 1.—Schematic of a GaN HEMT with Field Plate.

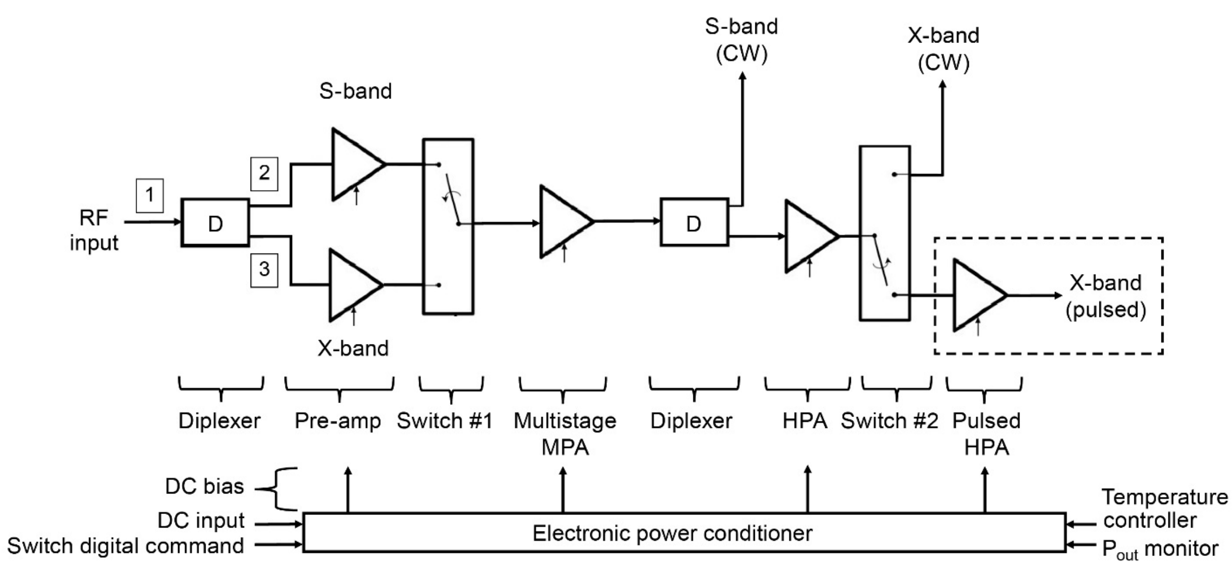

Figure 2.—Schematic of a reconfigurable fully solid-state microwave power module (SSMPM) based on high power GaN MMIC Power Amplifiers.

4.0 Measured Results

The following section briefly describes the individual components integrated into this POC physical realization. The measured performance of the diplexer, pre-amplifiers, SPDT switch, MPA, manual high power switch, and the HPA under pulsed operating conditions are presented previously in Reference 12.

The input diplexer is a Marki Microwave Model DPX-4. The pre-amplifiers Avantek models AWT-6035 operating from 2 to 6 GHz and model AMT-12436 operating from 7 to 12.4 GHz. The first stage of the wideband MPA is a Qorvo Model TGA2214-CP GaN MMIC that operates from 2 to 18 GHz. The second stage of the MPA is a Analog Devices Model HMC1087F10 GaN MMIC that operates from 2 to 20 GHz. The high efficiency CW HPA is a Qorvo TGF2978-SM with an advanced FP. The pulsed HPA is a Cree Model CGHV96100F2 GaN MMIC. The manual high power switch is a Ducomm model 2SM001. The input low power SPDT switch, shown in Figure 3 is an Analog Devices Model HMC1118 that operates over a wideband (9 kHz to 13 GHz).

4.1 GaN CW High-Power Amplifier (HPA) With Field Plate

The block diagram of the RF signal path is shown in Figure 4. The SSMPM version presented in Reference 12 consisted of two Sumitomo SGK77850-30A 20-W GaN HEMTs coupled together in a balanced configuration providing 40-W of P_{out} representing the HPA for X-band CW transmission. This new application of the SSMPM replaces the Sumitomo balanced amplifier with a Qorvo GaN transistor model TGF2978-SM, shown in Figure 5 that utilizes an advanced FP. This SSMPM is designed for operation at the NASA designated frequency for downlink on the DSN at 8.4 GHz, however, availability of the evaluation boards necessitates the characterization of the TGF2978-SM at the center frequency (f_0) of 9.1 GHz. The same device could be redesigned for operation at 8.4 GHz to suit a NASA specific application.

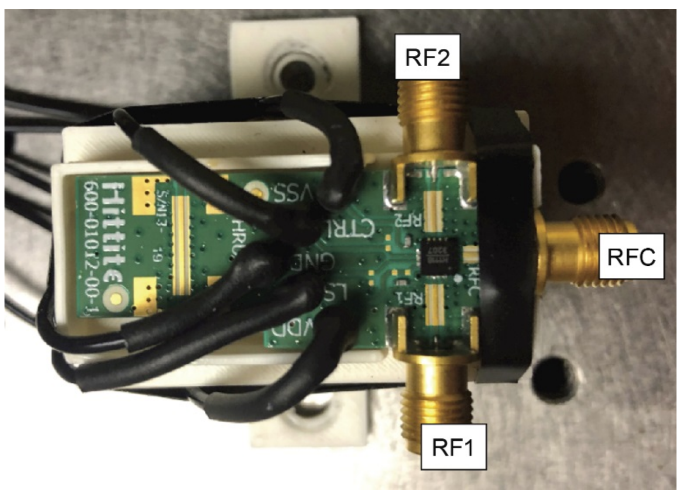

Figure 3.—SPDT Switch: Analog Devices Model HMC1118.

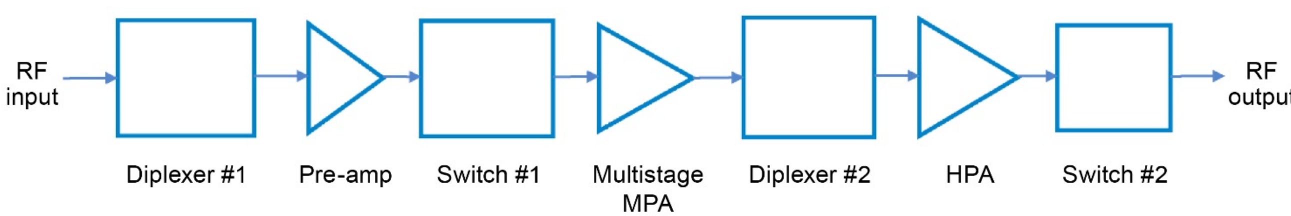

Figure 4.—RF signal path block diagram of SSMPM.

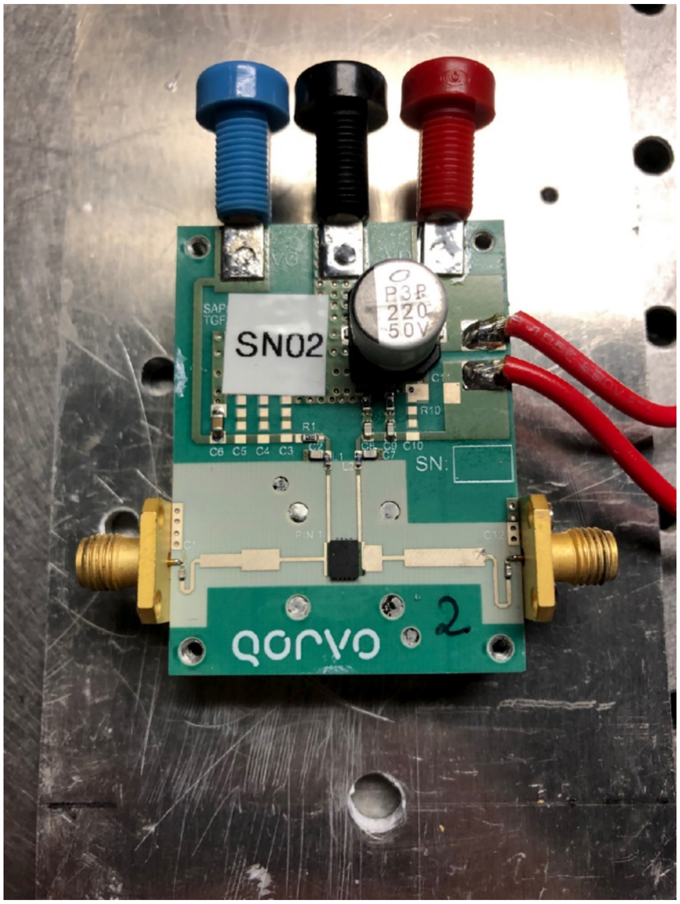

Figure 5.—HPA: Qorvo TGF2978-SM.

While the inclusion of a FP may result in an increase in C_{GD}, the Qorvos construction process TQGaN25 is optimized for power and efficiency (Ref. 13). The measured results for P_{out} and gain as a function of the input drive (P_{in}) at a fixed frequency of 9.1 GHz are presented in Figure 6 and the corresponding PAE also as a function of P_{in} is presented in Figure 7. The HPA delivers a P_{sat} of 43.3 dBm with a corresponding gain of 7.6 dB, and PAE of 46.6 percent, which is an improvement of 10.1 percent over the Sumitomo SGK77850-30A single amplifier.

P_{out} as a function of frequency over a 200 MHz band (9.00 to 9.2 GHz) is presented in Figure 8 and the corresponding PAE also as a function of frequency is presented in Figure 9. Over a 50 MHz (9.09 to 9.14 GHz) band, the HPA delivers a P_{out} > 17.4-W and the corresponding PAE > 46 percent. The reason for selecting a bandwidth of 50 MHz is because the designated bandwidth at X-band for NASA is 50 MHz. The maximum output power $P_{out(max)} \approx$ 20-W occurs at 9.115 GHz and the maximum efficiency $PAE_{max} \approx$ 50.4 percent occurs at 9.125 GHz. The measured P_{out} and gain as a function of frequency at a fixed P_{in} = 33.14–35.60 dBm with base plate temperatures as a parameter are presented in Figure 10. The corresponding measured PAE also as a function of frequency is presented in Figure 11.

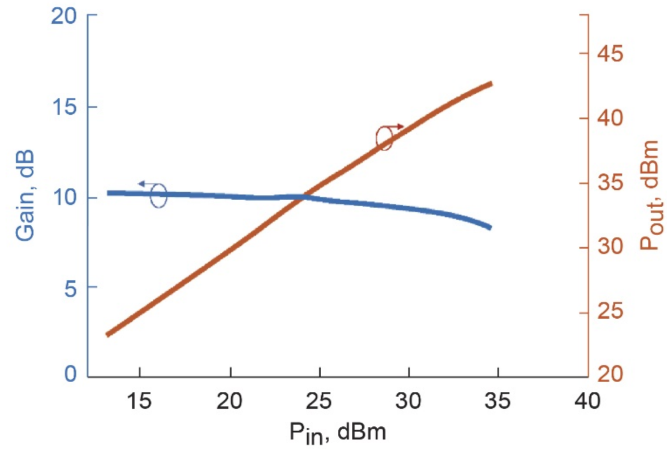

Figure 6.—Measured output power and gain as a function of the input drive at X-band (9.1 GHz), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25 °C.

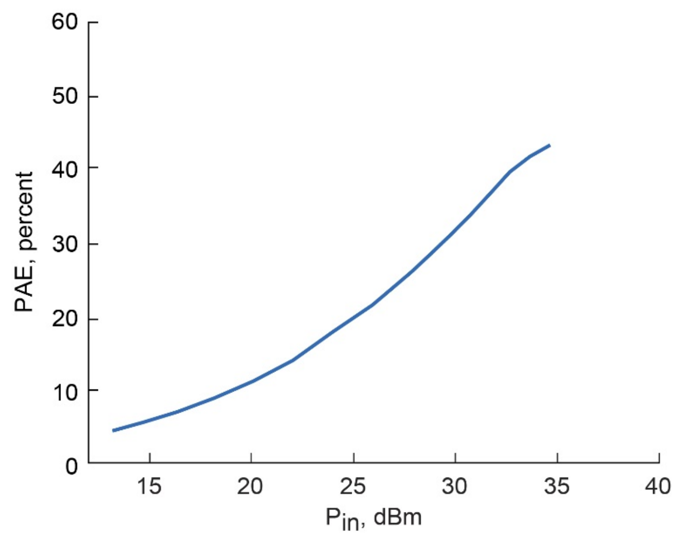

Figure 7.—Measured PAE as a function of the input drive at X-band (9.1 GHz), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25 °C.

Results on amplifier performance under varying temperatures, presented in Figure 10 and Figure 11 confirm the importance of heat management of HPAs. By maintaining a baseplate temperature below 20 °C we achieve an ≈ 1 dB increase in P_{out} and ≈ 1 dB increase in gain with a corresponding 5 percent increase in PAE than when operated at 25 °C.

A POC bread board version of the fully assembled SSMPM is shown in Figure 12 and measured output powers of the end-to end S-band, X-band (CW), and X-band (Pulsed) are shown in Figure 13.

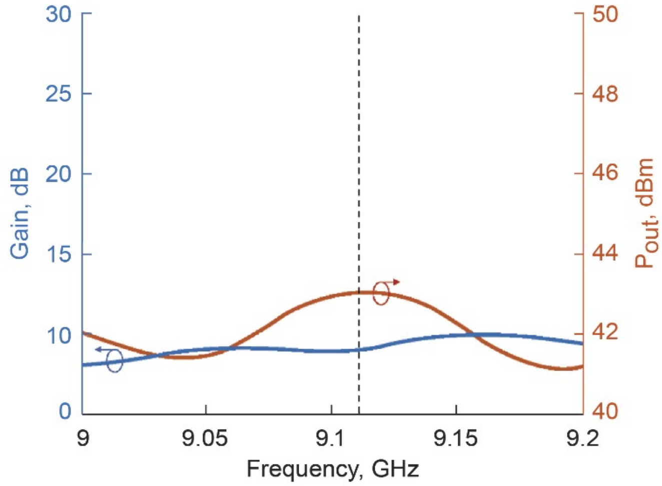

Figure 8.—Measured output power and gain as a function of frequency (P_{in} = 33.14–35.96 dBm), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25 °C.

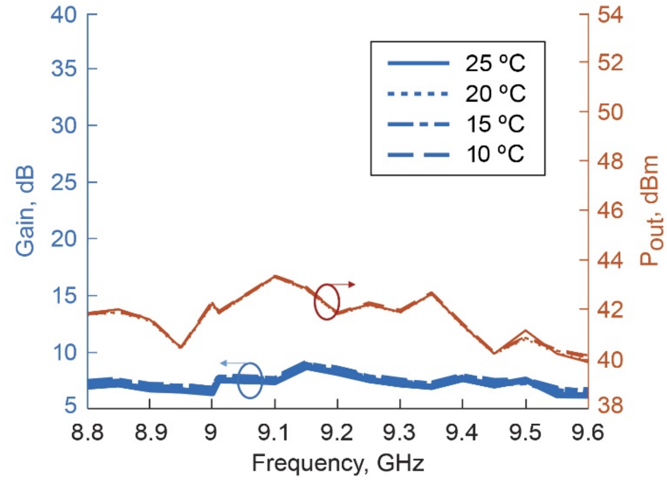

Figure 10.—Measured output power and gain as a function of frequency with baseplate temperature as a parameter (P_{in} = 33.14–35.96 dBm), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25, 20, 15, and 10 °C.

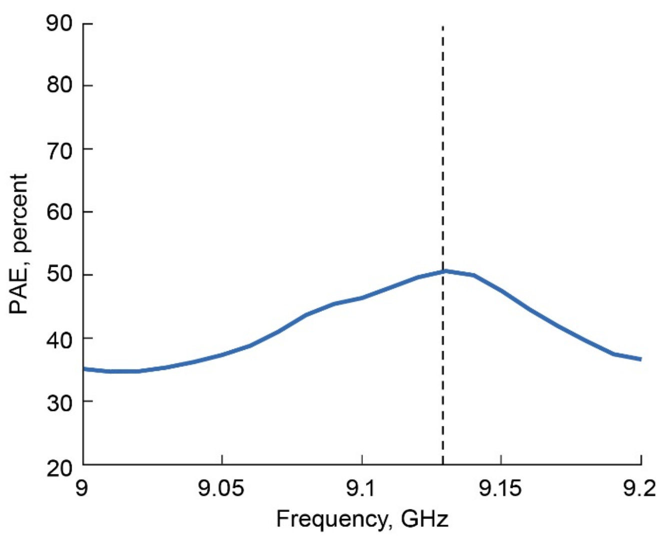

Figure 9.—Measured PAE as a function of frequency (P_{in} = 33.35–35.60 dBm), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25 °C.

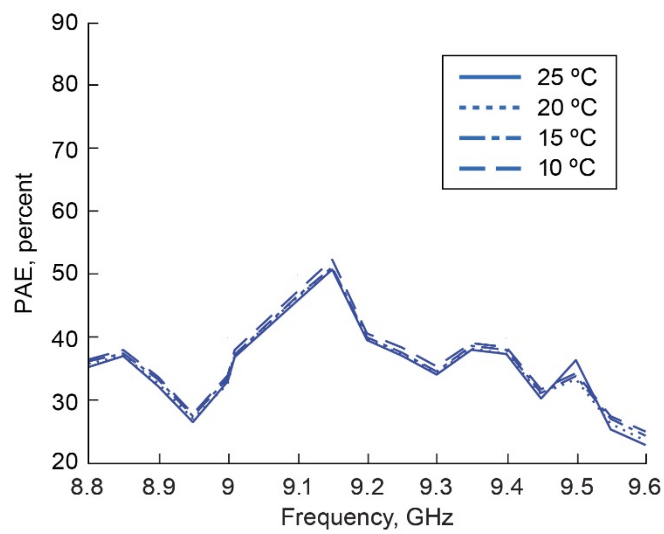

Figure 11.—Measured PAE as a function of frequency with baseplate temperature as a parameter (P_{in} = 33.14–35.96 dBm), for a single Qorvo TGF2978-SM-EVB01 with V_D = 32 V, V_G = –2.8 V, and I_{DQ} = 100 mA at 25, 20, 15, and 10 °C.

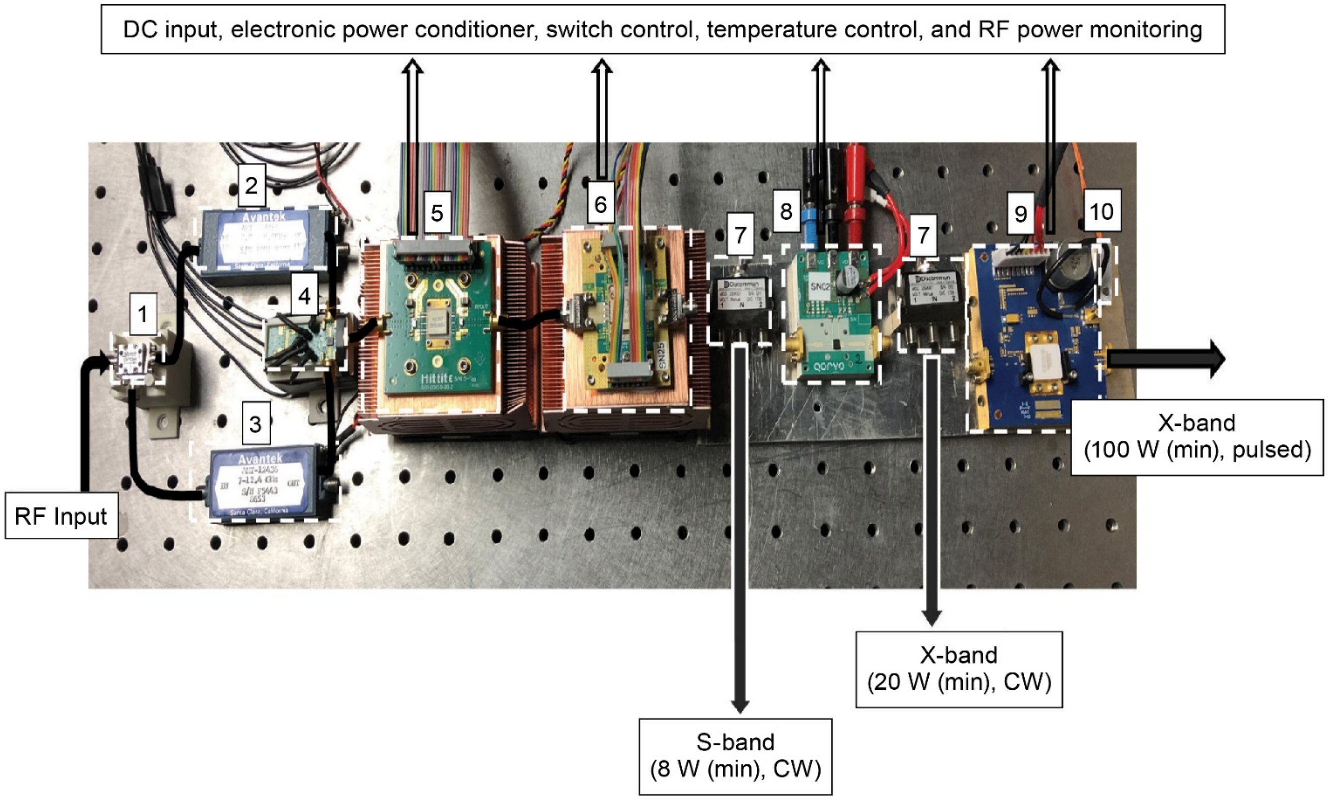

Figure 12.—A bread board POC version of the assembled dual band reconfigurable SSMPM. (1) Marki Microwaves DPX-4, (2) Avantek AMT-12436, (3) Avantek AWT-6035, (4) Analog Devices HMC1118 SPDT, (5) Qorvo TGA2214-CP, (6) Analog Devices HMC1087F10, (7) Ducommun 2SM001, (8) Qorvo TGF2978-SM, (9) Cree CGHV96100F2, (10) Thermocouple.

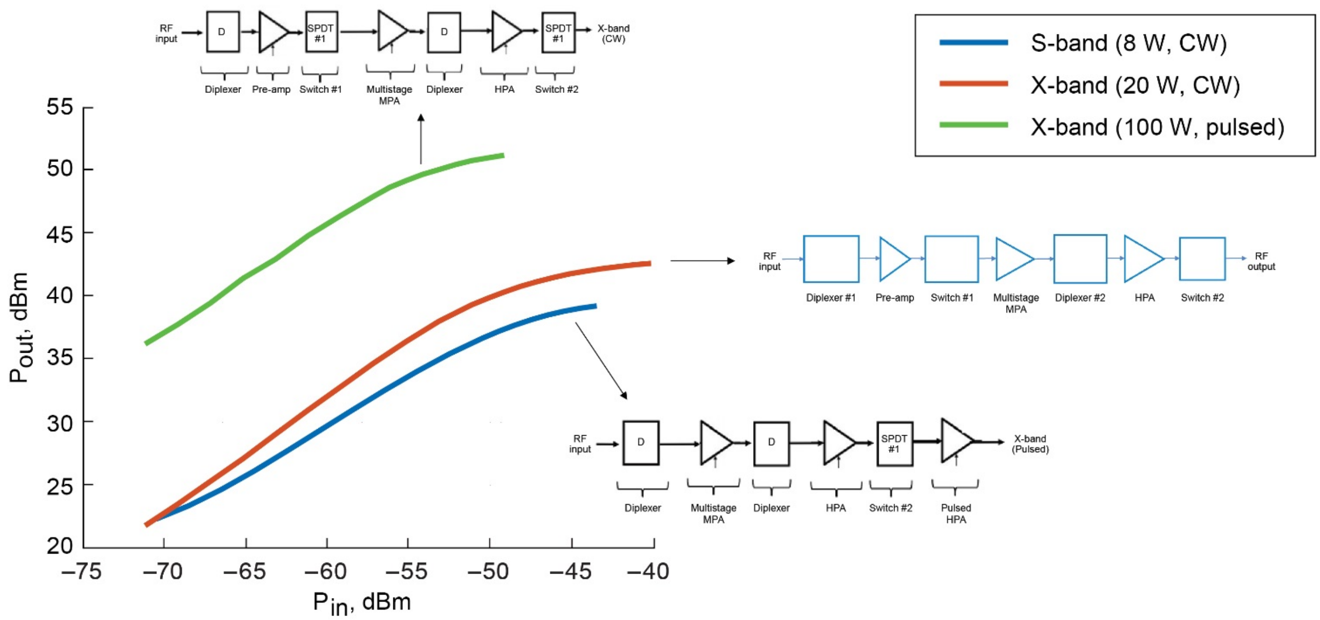

Figure 13.—Measured output power as a function of the input drive for the S-band (CW), X-band (CW), and X-band (Pulsed) signal pathways that are shown in the inset.

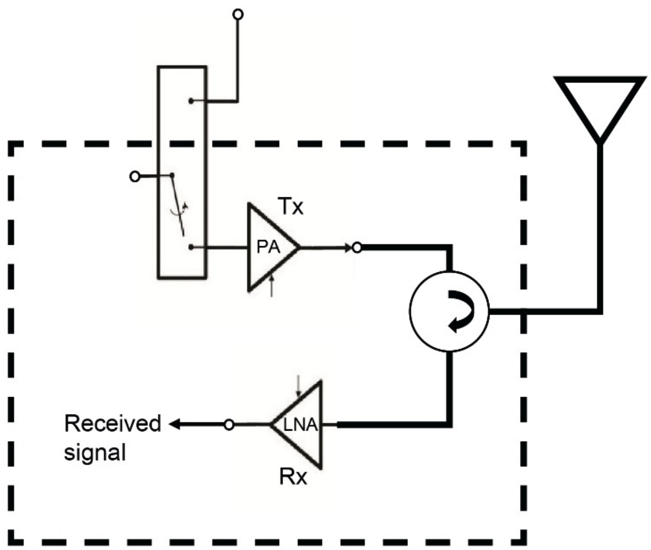

Figure 14.—Schematic of a T/R module integrated into the X-band Pulsed signal path of a SSMPM.

5.0 Radar Capabilities and Potential New Market

The functionality of the SSMPM previously presented in References 12 and 14, can be extended through upgrading the circuitry indicated within the dotted line in Figure 2 and replacing the PA with a T/R module (Figure 14) to enable both transmit and receive capability for X-band radar. We are in the process of characterizing the Qorvo QPM2637 T/R module for this application (Ref. 15). Additionally, if discrete PA and LNA are used then the circulator shown in Figure 14 can be an active chip circulator as described in Reference 16.

A potentially new application for the small size, light weight, high efficiency, multi-function SSMPM discussed above and cognitive vehicular radar (Ref. 17) is in the emerging urban air mobility market. The market is based on the electric vertical-takeoff-and-landing (eVTOL) vehicle concept that offers easy, affordable and clean transport for the traveling public. One of the enabling sub-system for eVTOL is the software-controlled electronically steered phased-array radar that can detect weather phenomena and can simultaneously scan and receive radar returns from aircrafts, ground vehicles, buildings and people (Ref. 18).

6.0 Conclusion

This paper presents the design, integration, and performance of a novel reconfigurable, GaN MMIC based SSMPM. The characterization of the individual components is supplemented with characterization of an alternative HPA in the form of a GaN HEMT that employs an advanced FP to increase device P_{out}, PAE and reliability. Expansion of the SSMPM topology to include new functionality has been proposed through the integration of a GaN T/R module into the X-band radar signal path.

This POC demonstration of the SSMPM shows an S-band CW chain that can deliver P_{sat} of 39 dBm (8 W) for TT&C, an X-band CW chain that can deliver P_{sat} of 43 dBm (20 W) for telecommunications, and the X-band pulsed chain without the pre-amplifiers can deliver P_{sat} of >50 dBm (>100 W) for radar applications.

This transmit power module is designed for use in CR which requires dramatic frequency and power reconfigurability. Through employing the X-band high power radar for proximity sensing this SSMPM can extend the CR system capabilities and increase the knowledge base of the surrounding environment.

References

1. P. Tilghman, “AI Will Rule the Airways,” IEEE Spectrum, pp. 28–33, June 2019.
2. S. Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications,” *IEEE Journal Selected Areas Communications*, vol. 23, no. 2, pp. 201–220, Feb 2005.
3. K. Entesari, P. Sepidband, “Spectrum Sensing,” *IEEE Spectrum*, pp. 51–73, June 2019.
4. J.X. Qiu, et al., “Vacuum Tube Amplifiers,” *IEEE Microwave Magazine*, vol. 10, no. 7, pp. 38–51, Dec 2009.
5. R.N. Simons and E.G. Wintucky, U.S. Patent No. 9,041,469 B1, “High-Efficiency Power Module,” May 26, 2015.
6. E. Illokken, “TWT Reliability in Space,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 2, no. 7, pp. 22–24, July 1987.
7. R. Strauss, “Orbital Performance of Communication Satellite Microwave Power Amplifiers (MPAs),” *International Journal of Satellite Communications and Networking*, vol. 11, no. 5, pp. 279–285, Sept/Oct 1993.
8. B.D. Weaver, et al., “On the Radiation Tolerance of AlGaN/GaN HEMTs,” *ECS Journal of Solid State Science and Technology*, vol. 5, no. 7, Q208-Q212, June 2016.
9. S. Karmalkar and U.K. Mishra, “Enhancement of Breakdown Voltage in AlGaN/GaN High Electron Mobility Transistors Using a Field Plate,” *IEEE Trans. Electron Devices*, vol. 48, no. 8, pp. 1515–1521, Aug 2001.
10. H.C. Chiu, C.W. Yang, H.C. Wang, F.H. Huang, H.L. Kao and F.T. Chien, “Characteristics of AlGaN/GaN HEMTs With Various Field-Plate and Gate-to-Drain Extensions,” *IEEE Trans. Electron Devices*, vol. 60, no. 11, pp. 3877–3882, Nov 2013.
11. B. Liao, Q. Zhou, J. Qin, and H. Wang, “Simulation of AlGaN/GaN HEMTs’ Breakdown Voltage Enhancement Using Gate Field-Plate, Source Field-Plate and Drain Field Plate,” *Electronics*, vol. 8, no. 8, April 2019, 406; https://doi.org/10.3390/electronics8040406
12. R.N. Simons, E.G. Wintucky, S.W. Waldstein, “A Novel Reconfigurable GaN Based Fully Solid-State Microwave Power Module for Communications/Radar Applications,” *2019 IEEE Aerospace Conference*, Big Sky, MT, March 2–9, 2019.

13. Qorvo, “TGF2978-SM, 20W, 32V, DC –12 GHz, GaN RF Transistor, General Description, Data Sheet,” 2015. [Online]. Available: https://www.qorvo.com/products/d/da004924 [Accessed 01st June 2019]
14. R.N. Simons, E.G. Wintucky, S.W. Waldstein, “A Novel Reconfigurable GaN Based Fully Solid-State Microwave Power Module for Communications/Radar Applications,” NASA/TM—2019-219933, July 2019.
15. Qorvo, “QPM2627 – 9- 10.5 GHz GaN T/R Module, Data Sheet” Oct 2019. [Online]. Available: https://www.qorvo.com/products/d/da006465 [Accessed 25th July 2019]
16. S.W.Y. Mung, W.S. Chan, “The Challenge of Active Circulators,” *IEEE Microwave Magazine*. vol. 20, no. 7, pp. 55–66, July 2019.
17. S. Feng and S. Haykin, “V2V Communication-Assisted Transmit-Waveform Selection for Cognitive Vehicular Radars,” 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), Edmonton, AB, Canada, May 5–8, 2019.
18. B. Carey. “Betting on Urban Air,” Aviation Week & Space Technology, vol. 181, no. 20, pp. 74–75, Oct. 14–27, 2019.