A Novel Reconfigurable GaN Based Fully Solid-State Microwave Power Module for Communications/Radar Applications

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Abstract—The paper presents as a proof-of-concept (POC) the design, integration, and performance of a novel reconfigurable S-/X-band, GaN based, fully solid-state microwave power module (SSMPM) to enable miniaturization of the overall RF system. The SSMPM includes diplexers, pre-amplifiers, a multistage medium power amplifier, SPDT switches, and CW/Pulsed high-power amplifiers. These components are synergistically integrated such that a single SSMPM is capable of being dynamically reconfigured to function as a CW S-/X-band amplifier for TT&C/science date downlink and as a pulsed X-band amplifier for remote sensing radar onboard a planetary exploration spacecraft. The POC SSMPM is capable of delivering Psat of 39 dBm (8 W CW) at S-band, Psat of 46 dBm (40 W CW) at X-band, and Psat of >50 dBm (>100 W Pulsed) at X-band.

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1. INTRODUCTION
Historically, the term microwave power module (MPM) is associated with a small fully integrated self-contained RF amplifier that combines both solid-state and microwave vacuum electronics technologies (Fig. 1) [1]. In this paper, we present the research and development of a novel fully solid-state microwave power module (SSMPM), which is distinctly different from the above MPMs [2]. The SSMPM advances the state-of-the-art in spacecraft transmitters. Our effort leverages from the recent advances in RF wide bandgap semiconductor (WBGS) crystal growth, wafer preparation, device/circuit fabrication technologies and reliability studies that have resulted from the investment that DARPA has made with the U.S. industry [3]. As a result of DARPA investments, the past few years have witnessed significant progress in the development of GaN high electron mobility transistor (HEMT) on silicon carbide (SiC) substrate based monolithic microwave integrated circuits (MMICs) for RF power applications. The main advantages of GaN HEMT on SiC substrate is that it has power density as high as 12.2 watts/mm at X-band [4]. Thus, for a desired output power a GaN MMIC is smaller in size compared to a GaAs MMIC. In addition, SiC substrate has 8 to 10 times higher thermal conductivity than a GaAs substrate [5], which allows operating at higher junction temperature and also enhances thermal reliability by more efficiently conducting waste heat away from the junction.

A typical payload on an Earth and planetary exploration spacecraft includes S-band system for telemetry, tracking, and command (TT&C) and a X-band or higher frequency telecommunication system for down linking data from science instruments. The role of the TT&C system is receiving commands and downlinking spacecraft house-keeping data. Typical science instruments are scatterometers, radiometers, and radar for synthetic aperture imagers. The role of the telecommunication system is to down-link science data acquired by these instruments. The current state of practice uses two separate S-band and X-band amplifiers in each of the above systems. However, due to the push for developing small satellites with enhanced system
capabilities/performance at lower cost, it is advantageous to
develop a single wideband, reconfigurable high-power, high-
efficiency SSMPM that can operate at multiple frequency
bands depending on the need at any given time. Additionally,
a single dynamically reconfigurable amplifier enables
miniaturization of the overall RF system. Innovations in
compound semiconductor materials, devices, and circuits to
increase the functionality and reconfigurable ability of RF
systems are reported in [6], [7].

In this paper, we present as a proof-of-concept (POC) the
design, integration, and performance of a novel
reconfigurable S-/X-band GaN based fully solid-state MPM
with a view to miniaturize the overall RF system. The module
synergistically integrates diplexers, pre-amplifiers, multistage medium power amplifiers (MPAs), SPDT
switches, and CW/Pulsed high power amplifiers (HPAs) with
a voltage sequencer, a DC blanking controller, and a low
voltage electronic power conditioner. The POC SSMPM
operates at both S-band and X-band to serve multiple roles.
The SSMPM can be reconfigured to deliver $P_{\text{sat}}$ of 39 dBm
(8 W CW) at S-band, $P_{\text{sat}}$ of 46 dBm (40 W CW) at X-band,
and $P_{\text{sat}}$ of >50 dBm (>100 W Pulsed) at X-band.

2. SOLID-STATE MICROWAVE
POWER MODULE

Module Design and Mode of Operation

The SSMPM layout is schematically illustrated in Fig. 2. The
typical frequencies at S-band and X-band for TT&C and
telecommunications are 2.2 GHz and 8.4 GHz, respectively.
At the input, a diplexer (D) selects either the S-band or the
X-band signal to be processed. The two pre-amplifier stages
are GaAs based MMIC amplifiers that amplify the S-band
and the X-band output signals from the diplexer respectively,
to a level appropriate to drive the common multistage MPA.
The switch is a non-reflective silicon single-pole, double
throw (SPDT) device. The multistage MPA is high efficiency
GaN HEMT PAs with output power ($P_{\text{out}}$) sufficient to drive
the HPA stage. The HPAs are also high-efficiency GaN
HEMT PAs that provide CW or pulsed power. As opposed to
conventional amplifiers with external input/output matching
networks, which take up relatively large area of dielectric
substrate for microwave circuitry, the MPA and the HPA are
designed with internally matched transistors that enables
miniaturizing the overall SSMPM [8].

An electronic power conditioner (EPC) provides the gate and
drain voltages and currents for the above amplifier stages.
The EPC is a DC-to-DC power convertor that transforms the
spacecraft bus voltage typically in the range of +21 V and
+35 V into regulated voltages required by the amplifier
stages. In addition, a DC power management circuit is
included to manage the correct power-up and power-down
sequence. That is to ensure that the negative gate voltages are
applied before the positive drain voltages are applied to turn
the amplifiers ON. Furthermore, a DC blanking control is
also provided to quickly turn the amplifiers OFF if a fault
condition arises. Moreover, a RF output monitor such as a
temperature sensor or a detector/reference diode pair is
located near or on the high-power GaN die, in the output
stage, to monitor for an over temperature condition. The
detector/reference diode pair also monitors the RF output
power level. The packaged SSMPM unit will be conduction
cooled.

![Figure 2. Schematic of a fully solid-state microwave power module (SSMPM) based on high power GaN MMIC Power Amplifiers.](image-url)
3. MEASURED RESULTS

In this section, the measured performance of the diplexer, pre-amplifiers, SPDT switch, MPA, and HPA under CW and pulsed operating conditions are presented. The MPA and the HPA were maintained at 25 °C base plate temperature during characterization by attaching them to Peltier-thermoelectric cold plate coolers.

**Diplexer**

The diplexer is Marki Microwave Model DPX-4 and is housed in a miniature connectorized package. The measured insertion loss from the input to the output low-pass (LP) (S-band) and the high-pass (HP) (X-band) coaxial ports are on the order of 0.8 dB and 1.0 dB at the S-band and X-band respectively. The passband return loss and the common port return loss are better than 10 dB. The isolation is better than 25 dB. These results are presented in Fig. 3.

**Pre-Amplifiers**

The two Avantek pre-amplifiers, model AWT-6035 operating from 2-6 GHz and model AMT-12436 operating from 7-12.4 GHz, each provides a gain of about 50 dB with output power and gain presented as a function of frequency in Fig. 4.

**SPDT Switch**

The switch is an Analog Devices Model HMC1118 and is a nonreflective single-pole, double-throw (SPDT) type that operates over a wideband (9 kHz-13 GHz), which allows reconfiguring the SSMPM to function at either S- or X-band. In addition, the switch is internally matched to 50 ohms at the RF input port and the RF output ports and hence requires no external matching components. The HMC1118 is housed inside a 3 x 3 mm surface mount package. The measured insertion loss of the switch when the two inputs are sequentially turned ON is on the order of 0.6 and 1.4 dB at S-band and X-band, respectively. The measured isolation between the two output ports of the switch is greater than 50 dB and 40 dB at S-band and X-band, respectively.

**Wideband GaN Multistage Medium Power Amplifier (MPA)**

The first stage of the wideband MPA is built with a Qorvo Model TGA2214-CP MMIC, which has 0.15 μm gate transistors fabricated on GaN-on-SiC substrate and operates from 2-18 GHz. The input and output RF ports of the MMIC have integrated DC blocking capacitors and are fully matched to 50 ohms. Furthermore, the MMIC package has pure copper base offering superior thermal management. The second stage of the MPA is built with Analog Devices Model HMC1087F10 GaN MMIC that operates from 2-20 GHz. The MMIC input and output ports are internally matched to 50 ohms. Moreover, the MMIC package body material is copper tungsten (15Cu85W). The measured P_{sat} and gain of each stage at S-band (2.15 GHz) and X-band (8.475 GHz) as a function of input power are presented in Fig. 5(a). The corresponding measured PAEs are presented in Fig. 5(b). The Psat of the first stage is 37 dBm, the corresponding gain is 20 dB, and the PAE is 25%. The P_{sat} of the second stage is 39.5 dBm, the corresponding gain is 8.8 dB, and the PAE is 27%.

**GaN CW High-Power Amplifier (HPA)**

The CW HPA stage is configured either as a single Sumitomo Model SGK77850-30A GaN high electron mobility transistor (HEMT) based MMIC amplifier or as two SGK77850-30A amplifiers in a balanced configuration. The MMIC amplifier is internally matched to 50 ohms. The balanced amplifier, with topology shown in Fig. 6 employs hybrid couplers (Narda Model 4356B, 2-18 GHz) at the input and output to divide and combine the power, respectively. The measured results are presented in Fig. 7. The P_{sat} of the single HPA is 43.5 dBm, the corresponding gain is 7.9 dB, and the PAE is 36.7%. The P_{sat} of the balanced HPA is 46.7 dBm, the corresponding gain is 6.8 dB, and the PAE is 34%.
Figure 5. (a) Measured output power and gain as a function of the input drive, and (b) Measured PAE as a function of the input power, for the MPA 1st stage with TGA2214-CP: $V_D = 22\, \text{V}$, $V_G = -2.3\, \text{V}$, $I_{DQ} = 600\, \text{mA}$ and 2nd stage with HMC1087F10: $V_D = 28\, \text{V}$, $V_G = -2.3\, \text{V}$, $I_{DQ} = 850\, \text{mA}$.

Figure 6. Balanced amplifier configuration consisting of two Sumitomo SGK77850-30A HPA and Narda Model 4356B hybrid couplers.

Figure 7. (a) Measured output power as a function of the input drive, and (b) Measured PAE as a function of the input drive at X-band (8.475 GHz), for a single Sumitomo SGK77850-30A with $V_D = 24\, \text{V}$, $V_G = -2.2\, \text{V}$, $I_{DQ} = 1750\, \text{mA}$ and balanced amplifier with $V_D = 24\, \text{V}$, $V_G = -2.2\, \text{V}$, $I_{DQ} = 3500\, \text{mA}$.
The pulsed HPA is realized with a Cree Model CGHV96100F2 MMIC, which has GaN HEMT on SiC substrate that are internally matched to 50 ohms. The MMIC is housed inside a metal/ceramic flanged package for optimal thermal performance. The measured characteristics under pulsed operating conditions is presented in Fig. 8. The $P_{\text{sat}}$ of the pulsed HPA is 50.86 dBm, the corresponding gain is 9.86 dB, and the PAE is 34.5%.

### 4. Proof-of-Concept (POC) Reconfigurable SSMPM and Test Results

A POC bread board version of the fully assembled reconfigurable SSMPM with the diplexer, pre-amplifiers, SPDT switch, MPA, and HPA presented earlier is shown in Fig. 9. The measured output power of the end-to-end S-band, X-band (CW), and X-band (Pulsed) chains are presented in Fig. 10. The signal pathways are shown in the inset in
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**Figure 10.** 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.

The results indicate that the S-band CW chain of the SSMPM delivers $P_{\text{sat}}$ of 39 dBm (8 W) for TT&C, the X-band CW chain delivers $P_{\text{sat}}$ of 46 dBm (40 W) for telecommunications, and the X-band pulsed chain without the pre-amplifiers delivers $P_{\text{sat}}$ of >50 dBm (>100 W) for radar applications.

**5. CONCLUSION AND DISCUSSIONS**

The paper presents as a proof-of-concept the design, integration, and performance of a novel reconfigurable, S-/X-band GaN MMIC based, fully solid-state microwave power module (SSMPM) with a view to miniaturize the overall RF system. The characterization of the individual components as well as the end-to-end performance of each of the S-band and X-band chains of the SSMPM are presented. These results indicate that the S-band CW chain can deliver $P_{\text{sat}}$ of 39 dBm (8 W) for TT&C, the X-band CW chain can deliver $P_{\text{sat}}$ of 46 dBm (40 W) for telecommunications, and the X-band pulsed chain without the pre-amplifiers can deliver $P_{\text{sat}}$ of >50 dBm (>100 W) for radar applications.

Leveraging upon compound semiconductor devices and novel materials [7] will enable the monolithic heterogeneous integration of GaN plus CMOS for realization of a compact SSMPM. The above results indicate that a single SSMPM is capable of being dynamically reconfigured to serve multiple roles such as an amplifier for TT&C, telecommunications, and radar onboard future Earth and planetary exploration spacecrafts.

As a final note, GaN HEMT based X-band power amplifiers when tested under conditions in low Earth orbit during a five-year mission, have shown to be tolerant to a total ionizing dose of 20k rads when placed inside a 2 mm thick aluminum shielding enclosure [9].

**REFERENCES**


**BIOGRAPHY**

**Rainee N. Simons** received the B.S. degree in electronics and communications engineering (E&CE) from the Mysore University, India, in 1972, and the M.Tech. degree in E&CE from the Indian Institute of Technology (IIT), Kharagpur, India, in 1974 and the Ph.D degree in electrical engineering from the IIT, New Delhi, India in 1983. He was a Senior Scientific Officer with the IIT, New Delhi, from 1979-1985. Dr. Simons was a National Research Council Post Doctoral Research Associate at NASA Glenn from 1985-1987. Since 1987 he is with the NASA Glenn Communications Technology Division. At NASA Glenn he served as the Chief of the Electron Device Technology Branch and as a Senior Microwave and Antenna Systems Engineer. Since November 2017, he is serving as the Program Officer for the Maturation of Instruments for Solar System Exploration (MatISSE) in the Planetary Science Division, NASA Headquarters, Washington, DC.

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