Demonstration of GaN HEMT MMIC High-Power Amplifier for Lunar Proximity Communications

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***Abstract*— In this paper, we demonstrate a high power, high efficiency, Ka-band (23.15 to 23.55 GHz) GaN HEMT MMIC based power amplifier for communications from the lunar orbit to lunar surface. The measured results include P_{out}, Gain, PAE, RMS EVM for Offset-QPSK, 8PSK, 16APSK, and 32APSK waveforms, 3rd-order IMD products, noise figure, and phase noise.**

Keywords—Ka-band, high power amplifier, gallium nitride MMICs, lunar orbit, lunar surface, lunar proximity communications

I. Introduction

The vision for NASA's Artemis mission is to enable human/robotic exploration of the Moon's surface/interior and provide a long-term presence on the Moon. To achieve this vision, NASA plans to develop a lunar Gateway to serve as an outpost, human landing systems and ascent elements for transporting the astronauts to and from the lunar surface, lunar relay satellites for communications, lunar surface habitats, lunar terrain vehicles, and pressurized rovers for exploring the lunar surface [1]. Additionally, NASA plan to use the commercial payload services for the transportation and deployment of science instruments and other payloads on the lunar surface. In the above missions, to ensure astronaut's health and safety and for transferring science data from surface instruments to Earth, NASA plans to deploy robust communication links between the lunar surface elements and the orbiting Gateway and relay satellites as illustrated in Fig. 1.

This paper builds on our prior and ongoing efforts in the development of Ka-band high efficiency gallium nitride (GaN) monolithic microwave integrated circuit (MMIC) based high-power amplifiers (HPAs). In these HPAs, the MMICs utilize GaN high electron mobility transistor (HEMT) technology that imparts several significant advantages over prior gallium arsenide (GaAs), Silicon Germanium (SiGe) and Silicon (Si) technologies. These include higher operating voltage, higher output power density, higher channel operating temperatures, and radiation hardness [2], [3], [4].

NASA's Projected Concept of Operation and Architecture (PCOA) for Space Communication and Navigation (SCaN) Networks for the next decade or two plans to use open and international standards to ensure interoperability and link connections that are cognitive to optimize throughput [5]. In view of the above, we recently demonstrated a prototype of a switched wideband GaN HEMT based MMIC HPA that operates across the 25.25 to 31 GHz frequency band for user spacecraft terminals to support interoperability [6]. Additionally, we investigated the benefits offered by GaN HPA's performance characteristics for user spacecraft cognitive radio platforms [7].

In this paper, we extend the above developments to the design and demonstration of a 23.15 to 23.55 GHz GaN HEMT based MMIC HPA. The HPA's performance is demonstrated in the context of future lunar proximity communication forward links that are planned between assets located in the lunar orbit and lunar surface such as, the landers, habitats, terrain vehicles, and rovers, and cross links between lunar relays. In [6], the performance of the 27 to 27.5 GHz return link is presented.

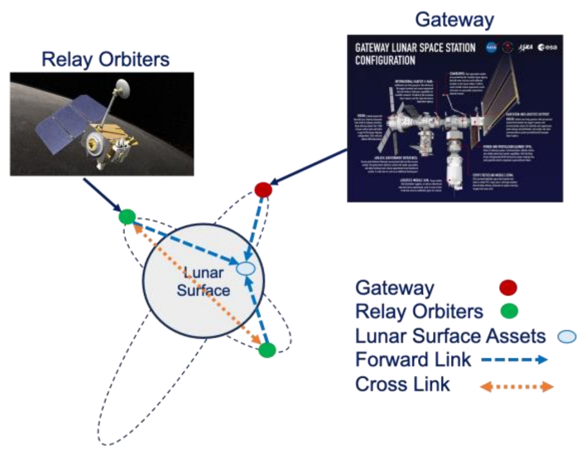

Fig. 1. Ka-Band High-Rate Lunar System Proximity Links.

II. HPA Design and Brief Set of Specifications

To demonstrate the HPA performance, a GaN MMIC driver amplifier chip and a power amplifier chip are assembled into two modules. The modules are interconnected to realize a protype HPA, as shown in Fig. 2, and overall microwave performance characterized. Brief set of specifications are:

- Operating frequency range: 23.15 to 23.55 GHz
- Output saturated power (P_{sat}): 7.5 to10 watts (CW)
- Power added efficiency (PAE): 20 to 25%
- Small signal Gain (drive & power amplifier): >25 dB
- RMS Error Vector Magnitude (RMS EVM): <6%
- Gain flatness: ±1 dB
- Input/output return loss: < -10.0 dB

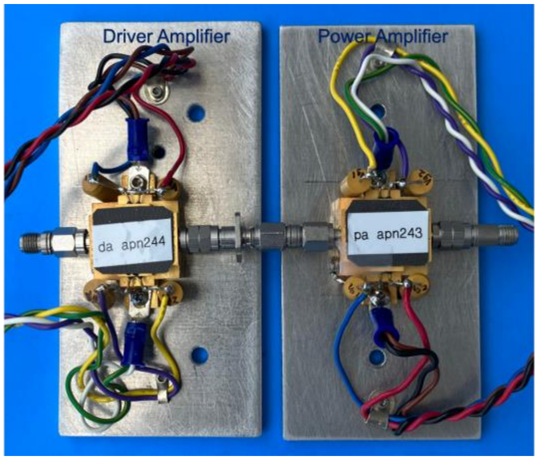

Fig. 2. Interconnected GaN MMIC driver and power amplifier modules. The GaN MMIC driver and power amplifier chips are Northrop Grumman APN244 and APN243, respectively.

III. KA-BAND HIGH POWER AMPLIFIER PERFORMANCE VALIDATION

The performance of the HPA is characterized using Rohde & Schwarz (R&S) SMW200A Vector Signal Generator, R&S FSW Signal and Spectrum Analyzer, Micronetics Noise Source, and Keysight N6705C DC Power Analyzer.

A. Output Power, Gain, and PAE

The measured P_{out} and Gain at the carrier or center frequency (f_0) of 23.35 GHz are presented in Fig. 3. The saturated output power (P_{sat}) and the small signal Gain are on the order of 38.8 dBm (7.6 watts) and 29.3 dB, respectively. The peak PAE is 20.0%. A similar set of results have been obtained at the lower and upper band edge frequencies of 23.15 and 23.55 GHz, respectively. To obtain P_{sat} greater than 38.8 dBm, two power amplifiers and a driver amplifier can be arranged in a balanced configuration as demonstrated in [7].

B. RMS Error Vector Magnitude (RMS EVM)

To demonstrate high data rate and bandwidth efficiency, the RMS EVM is measured at a fixed rate of 180 Msymbols per second for the Offset-QPSK, 8PSK, 16APSK, and 32APSK waveforms that are typically used in the transmission of data in satellite communications. The results achieved are presented in Fig. 4. At the 1-dB compression point, all waveforms can achieve RMS EVM of <6%. The measured spectrum for all four waveforms, when P_{in} is close to the 1-dB compression point, are presented in Fig. 5. The results indicate that the spectral efficiency for a fixed bandwidth (225 MHz) increases from 2 bits/s/Hz to 5 bits/s/Hz. Additionally, the spectrum is compliant with the NTIA mask. Furthermore, the out-of-band spectral regrowth measured at 1-symbol rate (180 MHz) away from the carrier or center frequency (f_0 = 23.35 GHz) for all four waveforms is less than –26 dBc. Hence, low adjacent channel interference or adjacent channel power ratio (ACPR).

C. 3rd-order Intermodulation Distortion (IMD)

In Fig. 6, the measured 3rd-order intermodulation intermodulation distortion products are presented to demonstrate good linearity. The data indicates that the output 3rd-order intercept point (OIP3) is on the order of 42 dBm.

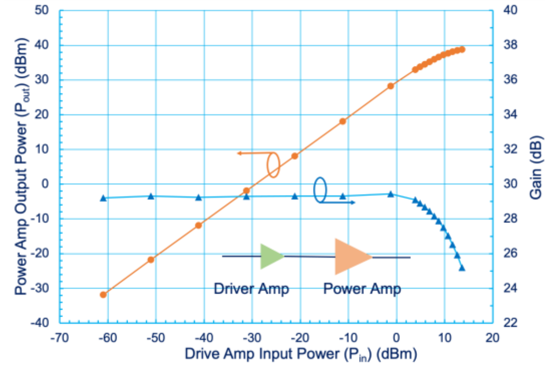

Fig. 3. Measured P_{out} and Gain vs. P_{in} of the interconnected driver (APN244) and power amplifier (APN243) modules at f_0 of 23.35 GHz. Driver amplifier: V_d =23.1 V and V_g = -3.9 V. Power amplifier: V_d = 23 V and V_g = -4.5 V. T = 25 °C.

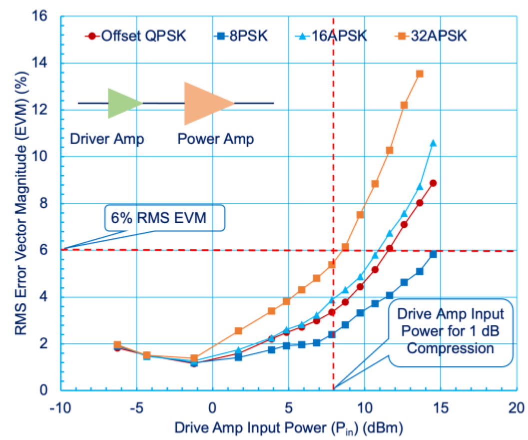

Fig. 4. Measured RMS EVM vs. P_{in} at f_0 of 23.35 GHz. The symbol rate is 180 Msymbols per second and square root raised cosine (SRRC) filter is set to 0.35.

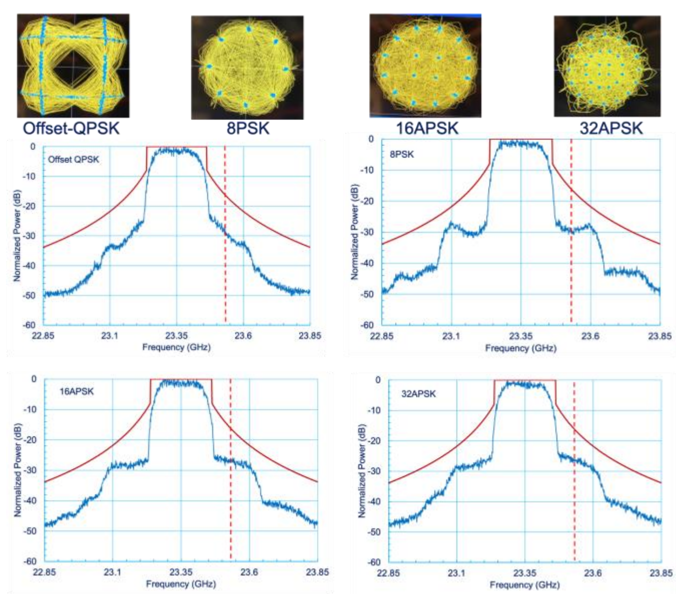

Fig. 5. Measured spectrum for Offset-QPSK, 8PSK, 16APSK, and 32APSK waveforms at f_0 of 23.35 GHz. Symbol rate is 180 Msymbols per second, SRRC filter is set to 0.35, and bandwidth is 225 MHz. The red solid line is the NTIA emission mask.

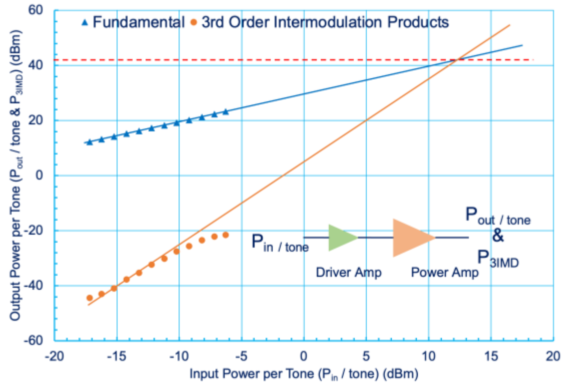

Fig. 6. Measured 3rd-order intermodulation distortion (IMD) vs. input power per tone. Tone spacing is 5 MHz.Tone frequencies are f_0 = 23.35 GHz ±2.5 MHz.

D. *Noise Figure (NF) and Associated Gain*

The measured NF and associated gain are presented in Fig. 7. The NF and the associated gain are on the order of <9.5 dB and 29 dB, respectively, across the 23.15 to 23.55 GHz range.

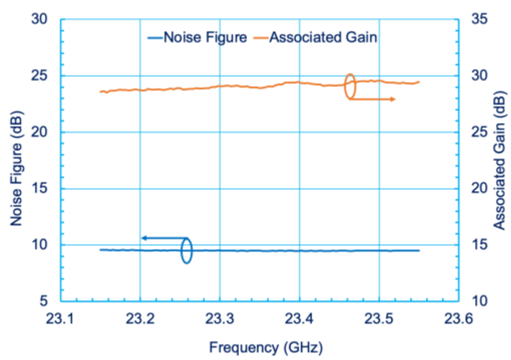

Fig. 7. Measured noise figure and associated gain vs. frequency.

E. *Single Sideband (SSB) Phase Noise*

The measured SSB phase noise spectral density is presented in Fig. 8. The SSB phase noise spectral density is compliant with the envelope defined by the MIL-STD-188-164C.

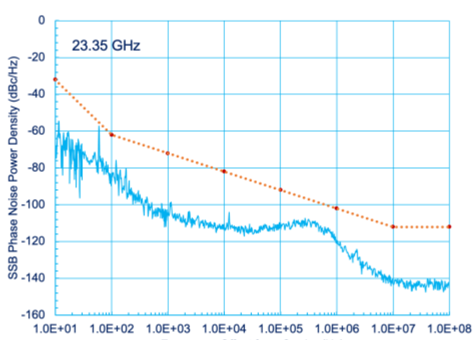

Fig. 8. Measured SSB Phase Noise spectral power density vs. the frequency offset from the carrier frequency. The carrier frequency is 23.35 GHz. The red dotted line is the MIL-STD-188-164C.

Conclusions And Discussions

The advantages of GaN for NASA's space applications is highlighted. The design and brief specifications for a 23.15 to 23.55 GHz GaN HEMT MMIC based HPA is presented. The design is validated by characterizing the interconnected driver and power amplifier modules. The measured P_{out}, Gain, PAE, RMS EVM for Offset-QPSK, 8PSK, 16APSK, and 32APSK waveforms, spectrum, 3rd-order IMD products, noise figure, and phase noise are presented and summarized in Table I. GaN HEMTS enable higher power density, higher PAE resulting in lighter, smaller, and more efficient RF/microwave systems in contrast with Si, SiGe, and GaAs based systems.

Table I. Summary of Test Results

Parameter	Measured Value
Carrier or Center Frequency (GHz)	23.35
Saturated Output Power (P_{sat}) (dBm)	38.8 (7.6 W)
Small Signal Gain (dB)	29.3
Peak PAE (%)	20.0
Return Loss (dB)	<-10.0
RMS EVM (Offset-QPSK, 8PSK,16APSK, & 32APSK) (P_{in} at 1-dB compression point) (%)	<6
Out-of-Band Spectral Regrowth (dBc)	<-26.0
OIP3 (dBm)	42.0
Noise Figure (dB)	<9.5
SSB Phase Noise Spectral Power Density (dBc/Hz) (P_{in} at the 1-dB compression point)	Compliant with MIL-STD Mask

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