Amplifier Output Power, Gain, Efficiency, and Bandwidth: A Comparative Study of GaN HEMT MMIC Multi-Stage Power Amplifiers versus Distributed Power Amplifiers

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Abstract

- In this paper we present first, the results of a study conducted to investigate the microwave performance of a wideband (25-31 GHz) GaN MMIC distributed high power amplifier (HPA)
- Second, we compare and contrast the above performance with that of an alternate architecture that relies on two HPAs to provide contiguous 25-31 GHz coverage. The two HPAs operate across 25-28 GHz and 27-31 GHz, respectively, and can be switched in and out depending on the need at any given time
- The parameters investigated includes the output power, gain, power added efficiency, bandwidth, RMS error vector magnitude for offset-QPSK, 8PSK, 16APSK, and 32 APSK waveforms, 3rd-order intermodulation distortion products, noise figure, and single sideband phase noise

Outline

- Introduction & Benefits of GaN MMIC Technology for HPAs
- Design Approaches for Wideband HPA & Brief Set of Specifications
  - Wideband (25-31 GHz) Distributed HPA
  - Switched HPAs for two contiguous frequency bands (25-28 & 27-31 GHz)
- Wideband Distributed HPA Characterization
  - Output Power & Power Added Efficiency (PAE) vs. Input Drive Power
  - Error Vector Magnitude (EVM) for OQPSK, 8PSK, 16APSK, & 32APSK Waveforms
  - Output Spectrum & Spectral Regrowth
  - Third-Order Intermodulation Distortion (IMD)Products
  - Noise Figure
  - SSB Phase Noise
- Performance Comparison of the above two approaches
- Conclusions & Discussions

Introduction

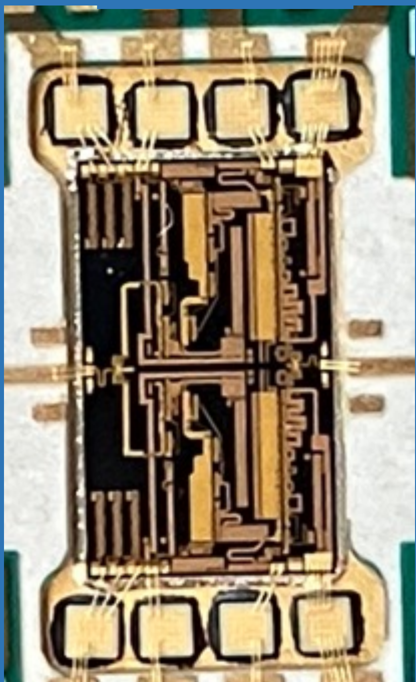
- NASA plans to transition the space relay communication services provided by TDRSS in a phased manner to U.S. commercial service provider networks
- This requires developing user spacecraft terminals capable of roaming and having performance flexibility to interoperate between multiple U.S. commercial service provider networks and space networks owned by U.S. government agencies
- However, legacy systems operate over different frequency bands within the Ka-band spectrum
- Hence, there is a need to develop wideband microwave components and HPAs

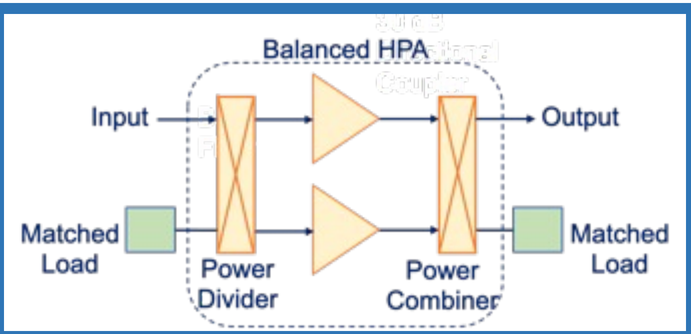
Benefits of GaN Technology for Microwave High Power Amplifiers

- Gallium nitride (GaN) has large bandgap, high electron saturation velocity, excellent thermal properties, & good chemical stability
- Consequently, high electron mobility transistors (HEMTs) fabricated on epitaxially grown GaN-on-SiC wafers can
  - Operate at high frequencies
  - Deliver high RF output power hence fewer devices for a target output power – smaller size, lower mass
  - Offer good linearity
  - Provide high power added efficiency
  - Perform at elevated temperatures
  - Operate in high radiation environment

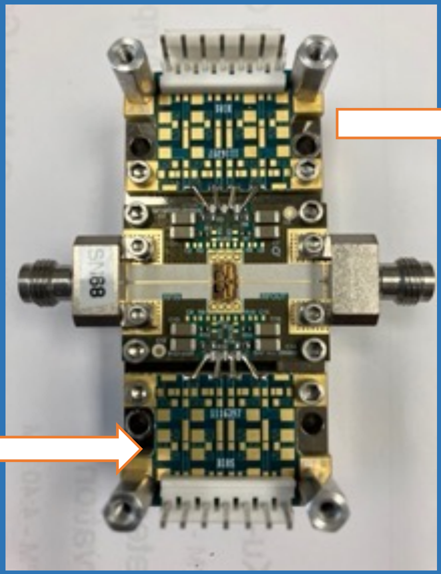
1st Design Approach — GaN Wideband Distributed HPA Proof-of-Concept Demonstration Model

GaN MMIC

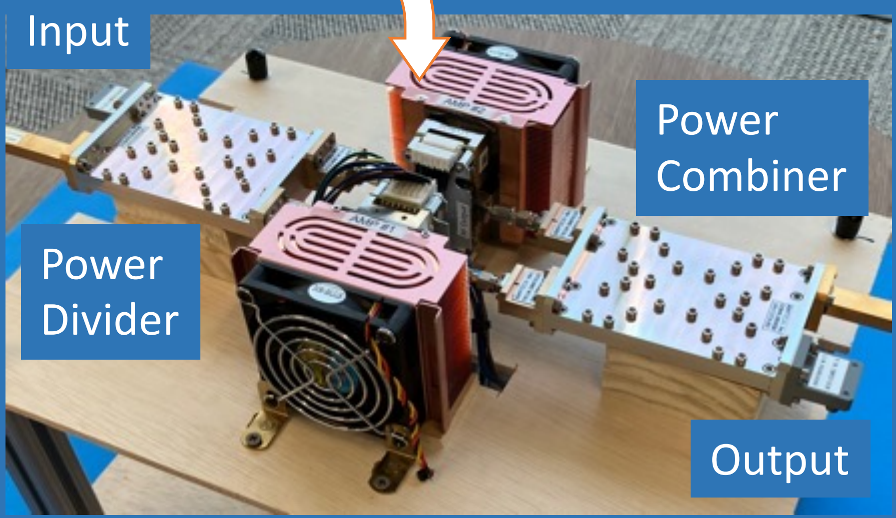




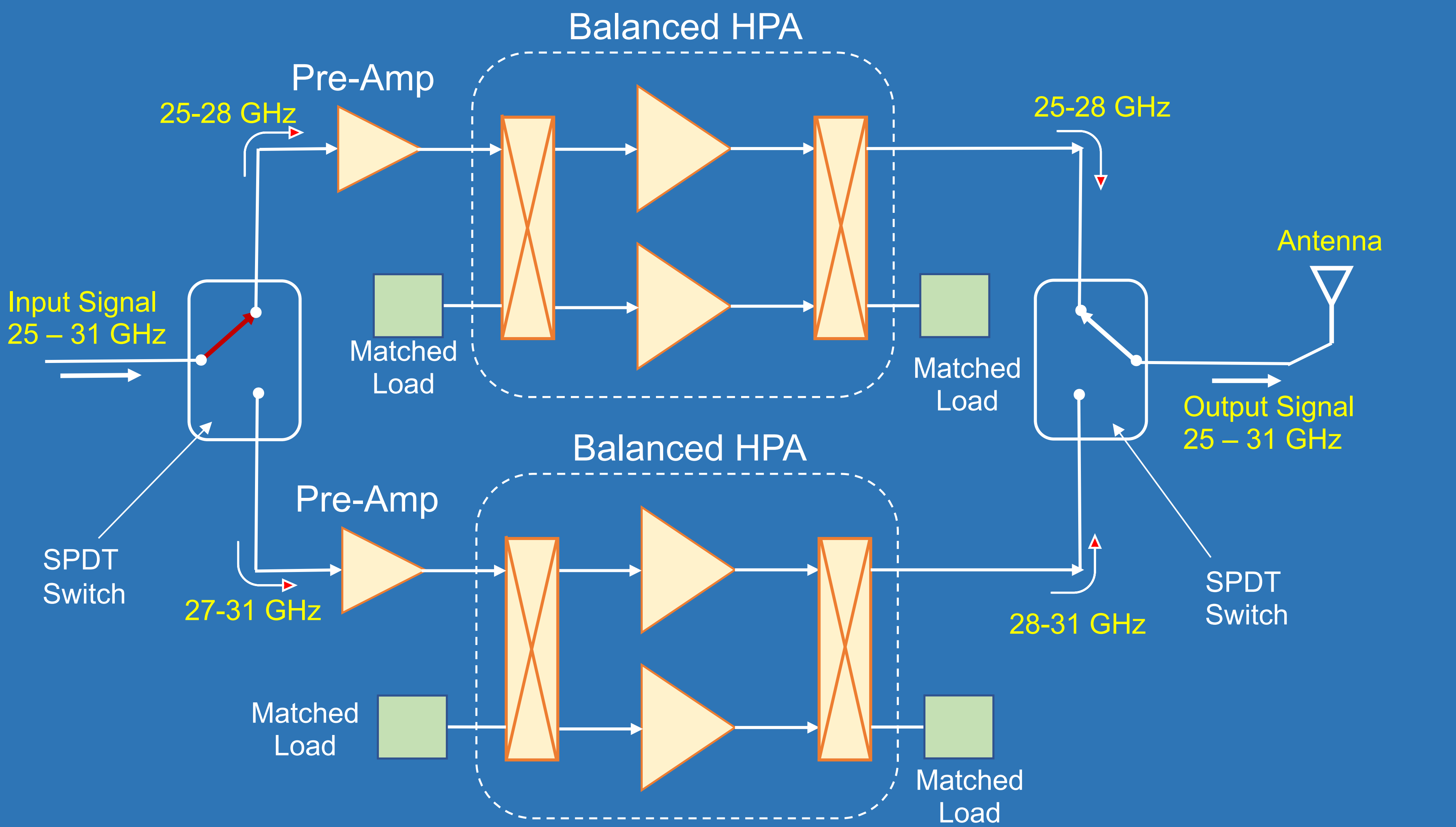
GaN MMIC
In Test Fixture



Test Fixture
attached to a
Heat Sink with Fan



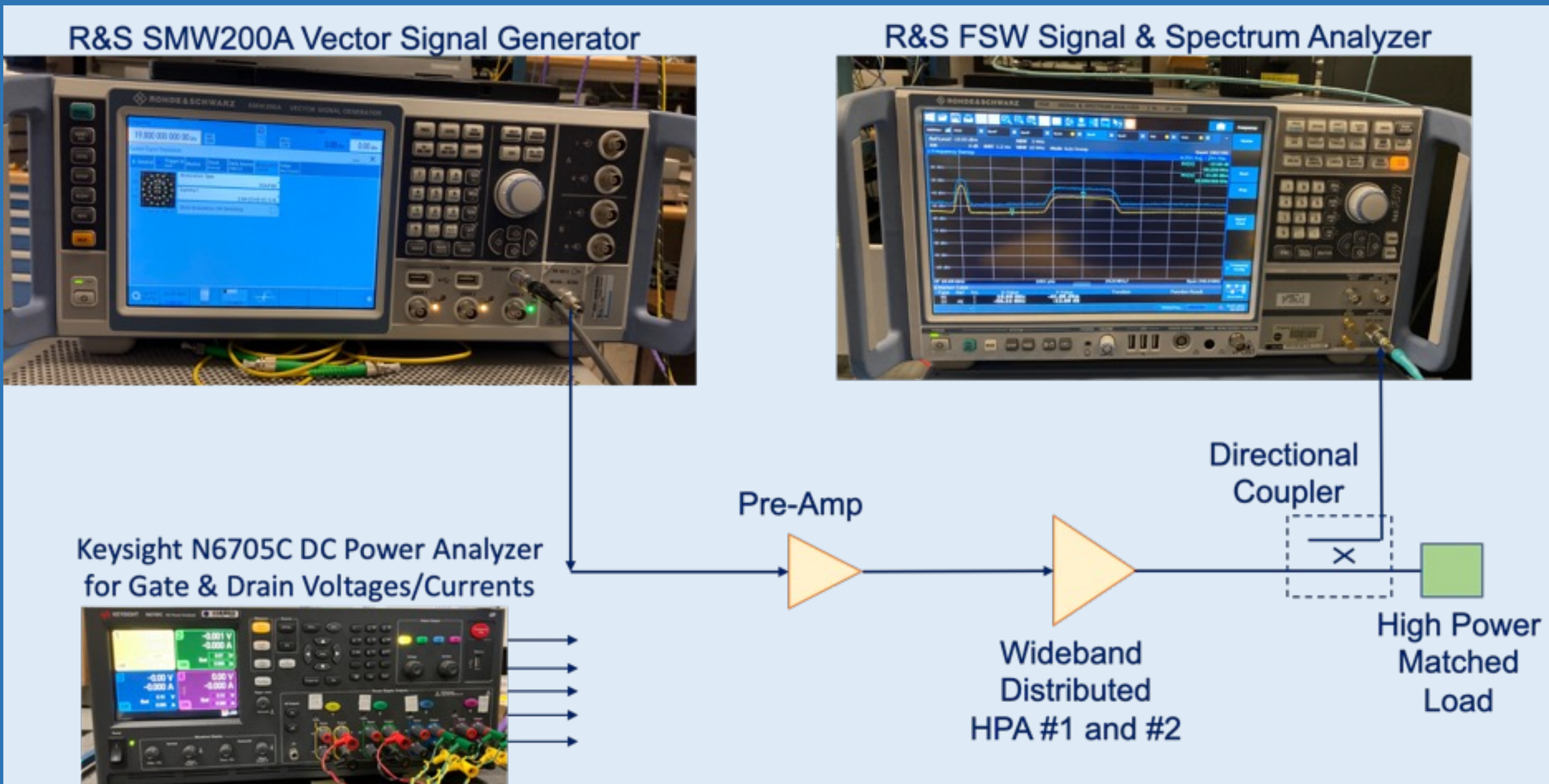
2nd Design Approach — GaN Switched HPAs for Two Contiguous Frequency Bands (25-28 GHz & 27-31 GHz)



Brief Set of Specifications for GaN Wideband Distributed & Switched HPAs

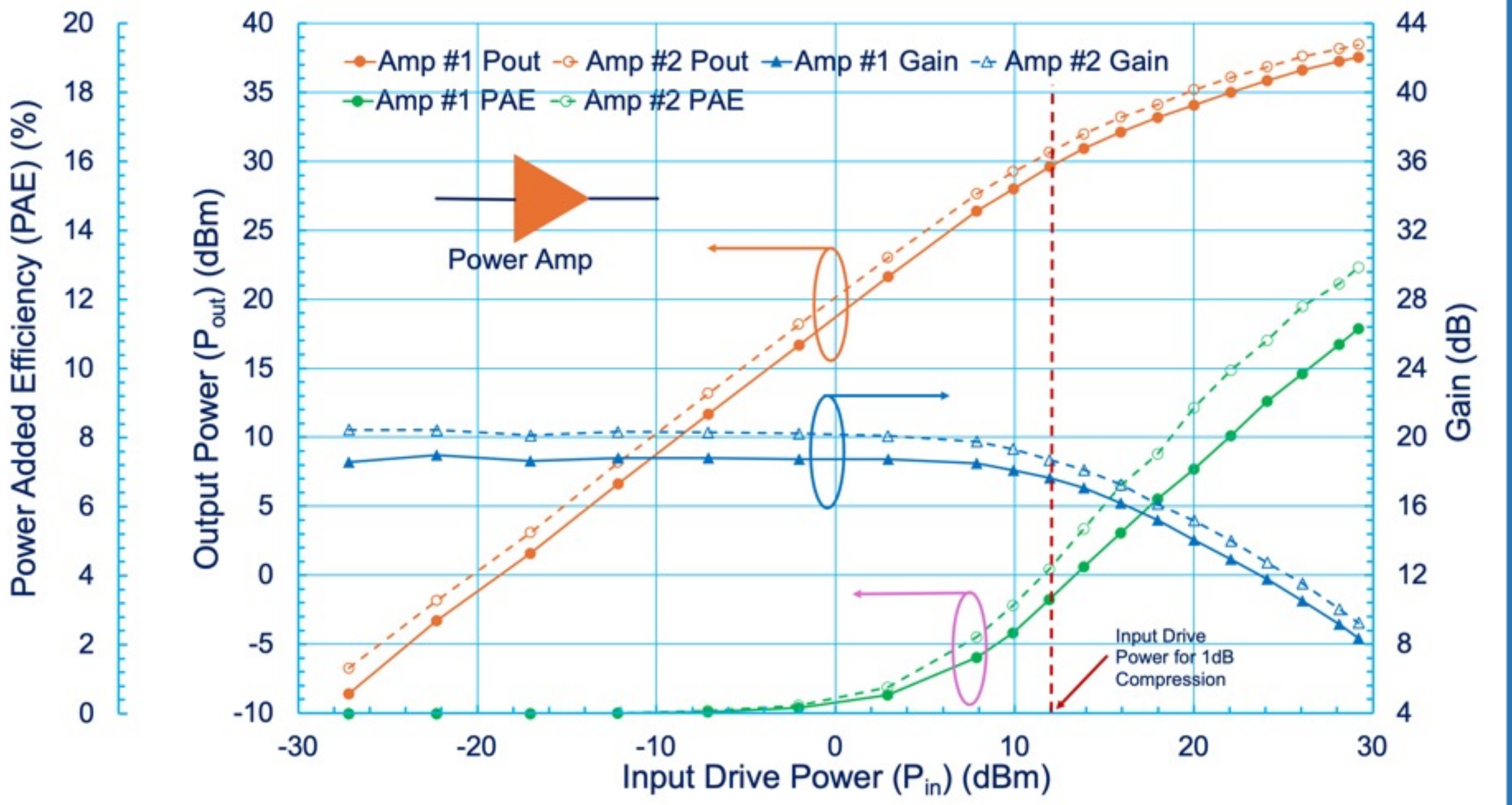
- Saturated output power (P_{sat}) (Single Amp): 8 to 10 W (CW)
    - ~3dB higher for Balanced Amplifier
- Bandwidth: 25 to 31 GHz
- PAE: 15 to 20 percent
- Small signal gain: 15 to 20 dB
- Input/output return loss: < –10.0 dB
- Gain flatness over full bandwidth: ± 1 dB

Test Setup for GaN Wideband Distributed HPA Characterization



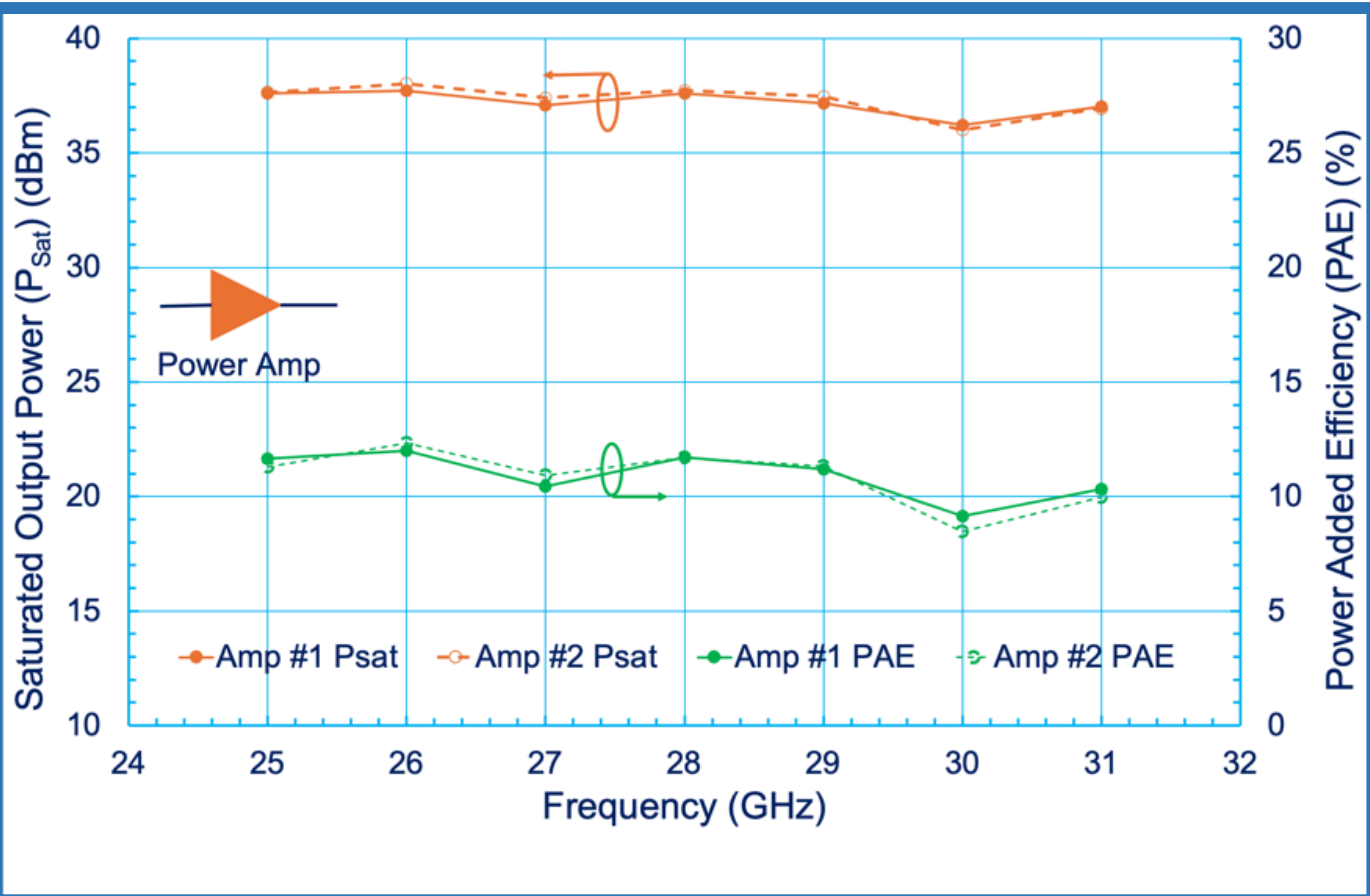
Measured P_{out}, Gain, & PAE vs. P_{in}

(f_0 = 28.0 GHz. $V_{d1} = V_{d2}$ = 18 V, V_{g1} = –2.0 V, V_{g2} = –2.04 V, T = 25 ° C)



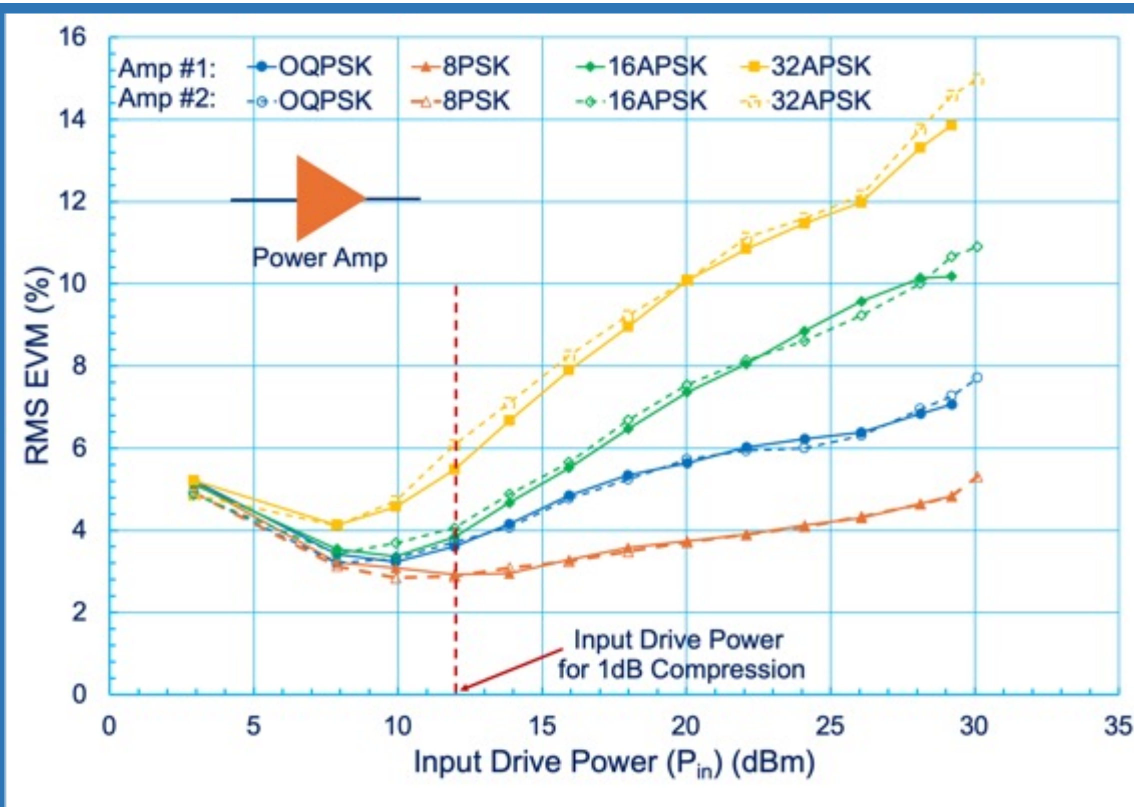
Measured P_{sat}, & PAE vs. Frequency

(f_0 = 28.0 GHz. $V_{d1} = V_{d2}$ = 18 V, V_{g1} = –2.0 V, V_{g2} = –2.04 V, T = 25 °C)

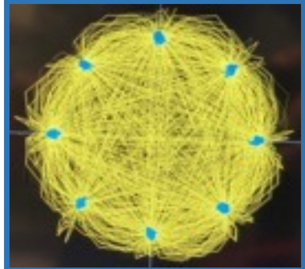


Measured RMS EVM vs. P_{in}

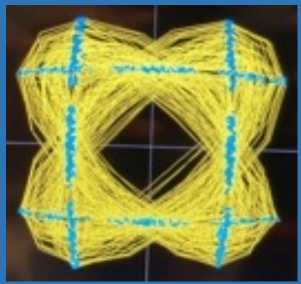
(F_0 = 28 GHz, Symbol Rate:180 Msymbols/second & Square Root Raised Cosine (SRRC) filter set to 0.35)



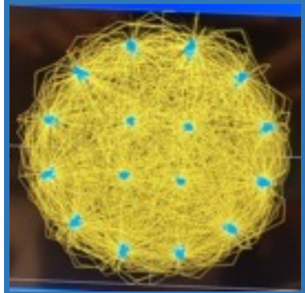
Waveforms & Constellations



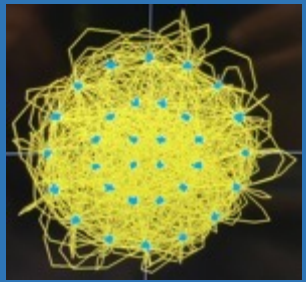
8PSK



Offset-QPSK



16APSK

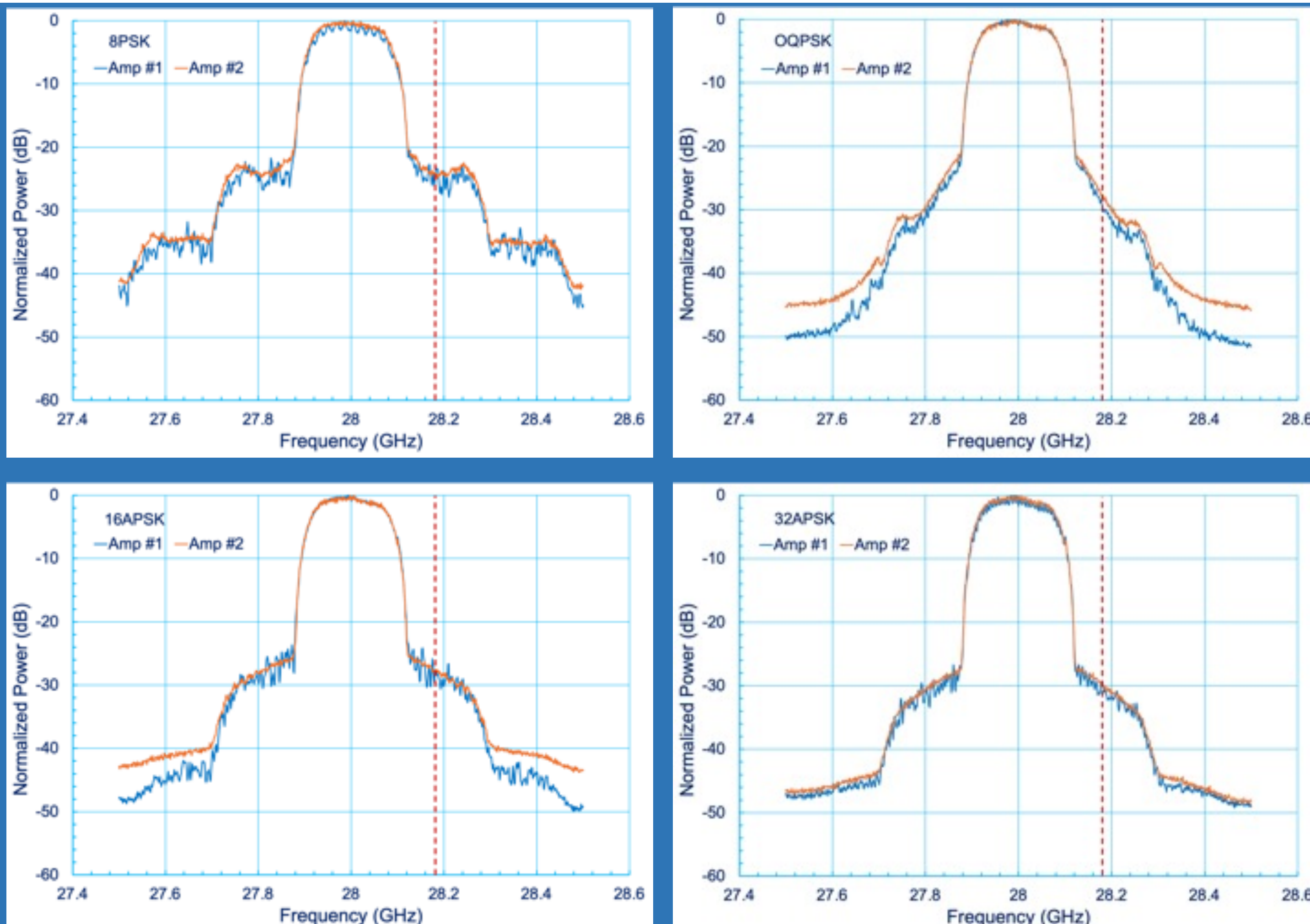


32APSK

✓ Low RMS EVM (≤ 6%) up to the 1-dB compression point demonstrates excellent linearity, which enables amplifying higher-order modulation waveforms, such as 8PSK,16APSK, & 32APSK. This feature enables the spacecraft radios to support both CCSDS compliant waveforms used by NASA missions, as well as, DVB-S2 waveforms typically used by commercial service providers

Measured Spectrum @ ~5% EVM

(F_0 = 28 GHz, Symbol Rate: 180 Msymbols/second, SRRC filter: 0.35, & Channel Bandwidth: 225 MHz)



✓ For a fixed bandwidth the spectral efficiency improves from 2bits/s/Hz (OQPSK) to 5bits/s/Hz (32APSK) & can be exploited by spacecraft radios to enhance throughput

Measured Out-of-Band Spectral Regrowth

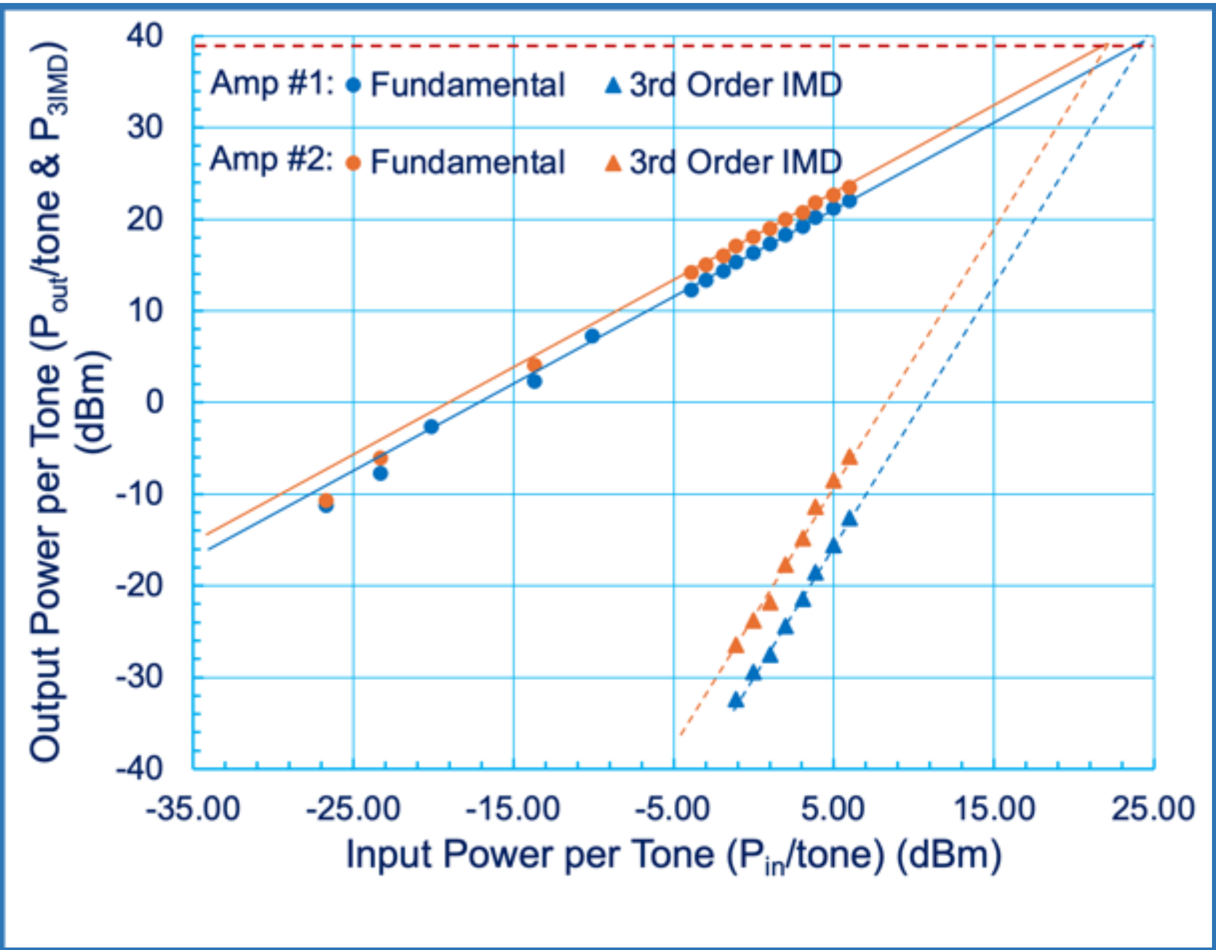
- ✓ The out of band spectral regrowth is measured at 1-symbol rate (180 MHz) away from the center frequency or carrier frequency (28 GHz) for all four waveforms and the results are summarized below

Waveform	Spectral Regrowth (dBc) (@28.18 GHz)	
	Amp #1	Amp #2
8PSK	-26.1	-24.3
OQPSK	-29.6	-27.9
16APSK	-29.5	-27.6
32APSK	-29.4	-30.0

- ✓ The data indicate spectral regrowth <–20 dBc, which demonstrates low adjacent channel interference or adjacent channel power ratio (ACPR). A spacecraft radio with this capability enables roaming & interoperability

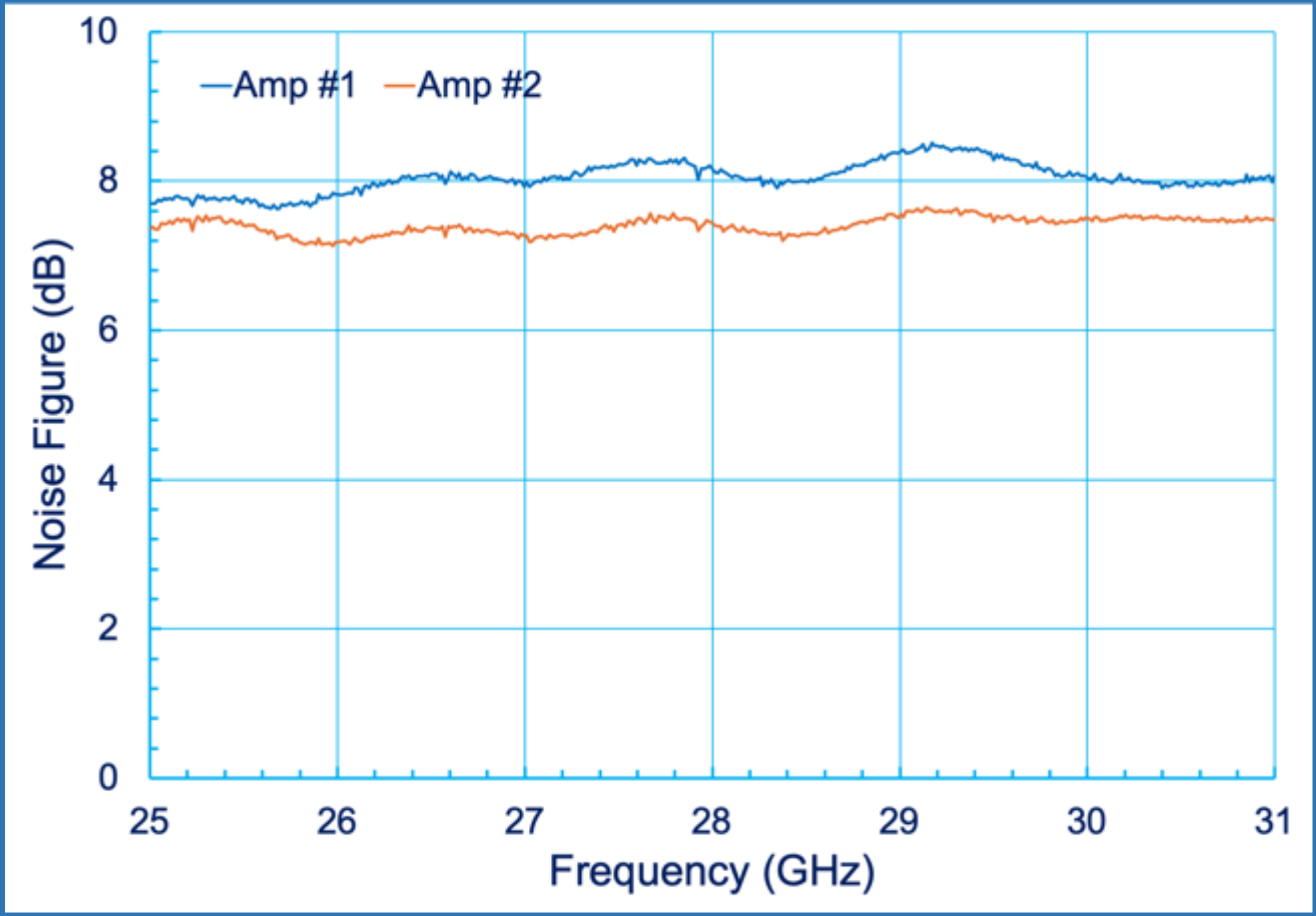
Measured 3rd-Order Intermodulation Distortion (IMD) vs. P_{in} per Tone

(Tone Frequencies: 28 GHz ± 2.5 MHz & Tone Spacing: 5 MHz)



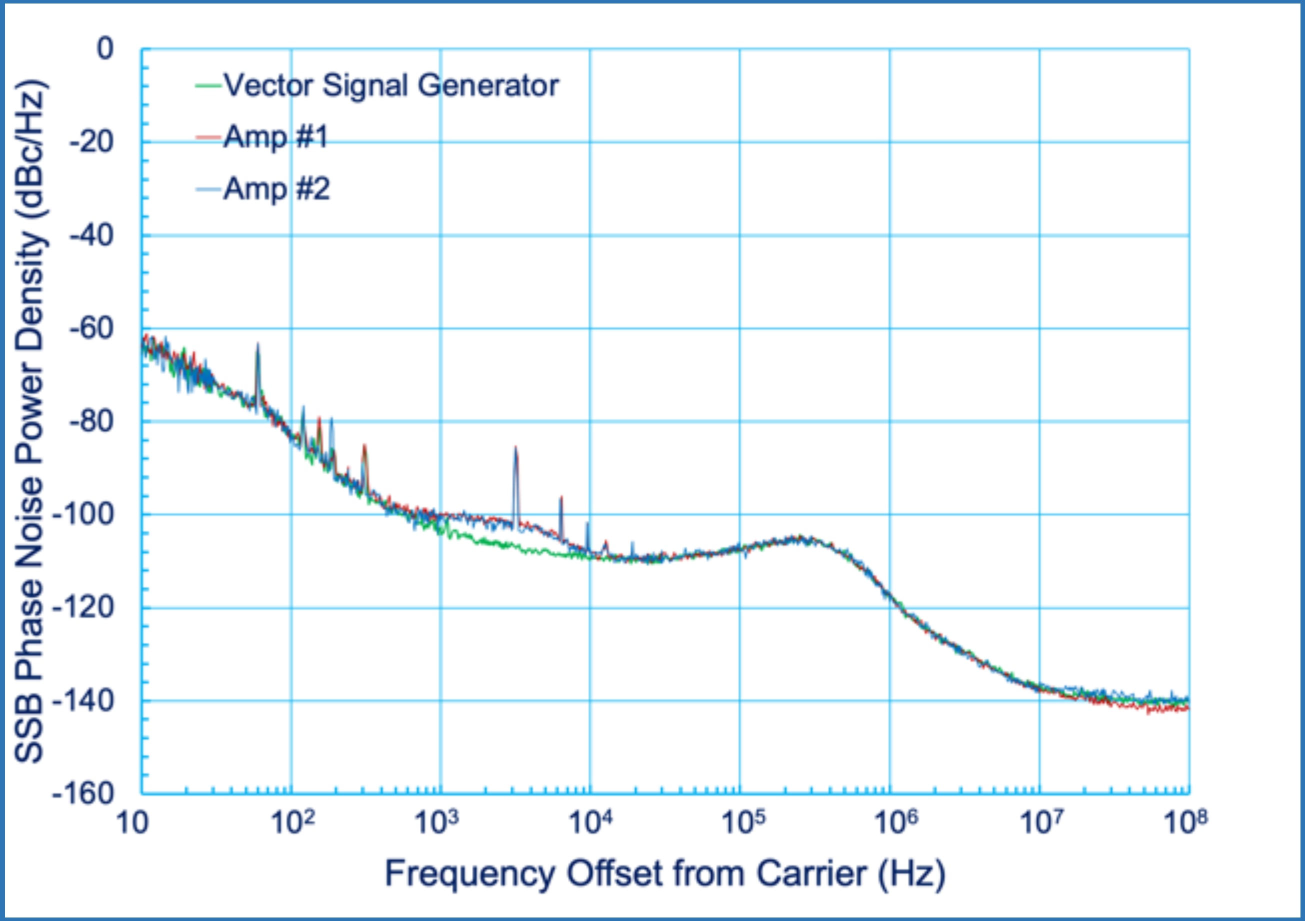
✓ The high OIP3 of 39 dBm demonstrated that the 3rd-order IMD products generated is small. Hence, interference signals generated within the spacecraft radio channel bandwidth due to HPA nonlinearity is also small

Measured Noise Figure vs. Frequency



✓ Low noise figure (≤9.0 dB), while the spacecraft radio is transmitting, implies less S/N ratio degradation of the adjacent channels

Measured SSB Phase Noise Spectral Power Density vs. Frequency Offset from f_0 = 28 GHz



- ✓ Low HPA phase noise implies less rotation of the waveform constellation points which improves BER performance of the spacecraft radio

GaN Wideband Distributed HPA Performance Summary

Parameter	Amp #1 Measured Value	Amp #2 Measured Value
Frequency Range (GHz)	28±3.0	28±3.0
Output Power (P_{sat}) (dBm)	37±0.75 (5.1±0.9 W)	37±1 (5.15±1.15 W)
Small Signal Gain (dB)	19.0±0.4	19.4±0.7
Peak PAE (%)	10.5±1.5	10.4±2
Gain at peak PAE (dB)	8.2±0.2	8.6±0.6
Return Loss (dB)	< –10.0	< –10.0
RMS EVM Offset-QPSK, 8PSK, 16APSK, and 32APSK (Drive at 1-dB compression point and carrier frequency of 28 GHz)	≤ 6%	≤ 6%
Out-of-Band Spectral Regrowth (dBc), @ 28.18 GHz	< –26.0 dBc	< –24.0 dBc
OIP3 (dBm) at carrier frequency of 28 GHz	39	39
Noise Figure (dB) across the above frequency range	< 8.6	< 7.7

GaN Switched HPAs Performance Summary

Parameter	Measured Value (25–28 GHz Driver & Power Amp)			Measured Value (28–31 GHz Driver & Power Amp)		
Frequency (f_0 and $f_0 \pm 1.5$ GHz)	25.0	26.5	28.0	28.0	29.5	31.0
Output Power (dBm) (P_{sat})	39.1	37.7	37.9	37.5	38.4	37.0
Small Signal Gain (dB)	30.9	29.6	30.4	30.5	31.4	29.7
PAE (%)	22.8	18.9	19.0	21.5	23.3	20.6
Return Loss (dB)	< –10.0			< –10.0		
RMS EVM (%) (drive at 1-dB compression point) (QPSK, Offset-QPSK, 8PSK, 16APSK, & 16QAM)	5 (All but 16QAM) 7 (16QAM)			5 (QPSK & 8PSK) 6 (Offset-QPSK & 16APSK) 10 (16QAM)		
Out-of-Band Spectral Regrowth (dBc)	< –30			< –30		
OIP3 (dBm)	48			53		
Noise Figure (dB)	9 (Higher NF due to stabilizing gate resistor)			7		
SSB Phase Noise Power Density (dBc/Hz) (drive at 1-dB compression point)	Compliant with MIL-STD Mask Added Phase Noise is insignificant			Compliant with MIL-STD Mask Added Phase Noise is insignificant		

Conclusions & Discussions

- Characterization of the Wideband Distributed HPA and the Switched HPA indicates:
  - Both HPA design approaches are capable of providing wideband performance
  - The linearity, spectrum, spectral regrowth, noise figure and SSB phase noise characteristics are comparable for both approaches
  - The PAE of the wideband distributed HPA is lower than the switched HPAs
- The single wideband distributed HPA approach requires few components — simplifies HPA design, manufacturing, & testing — lower size, mass, & cost