Wide Bandgap Semiconductor Devices & Systems for Communications in Extreme Environment

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Motivation

- Strategic objective of the Planetary Science Division within NASA's SMD is to advance scientific knowledge of the origin and history of the solar system
- The scientific foundation for this endeavor is the planetary science decadal survey
- The decadal survey besides other investigations prioritizes the study of the inner planets and the giant planets of our solar system
- These include Venus and Jupiter and its icy Moons
- Venus may be volcanically active. Jupiter's icy moons harbor oceans below their ice shells: conceivably Europa's Ocean could support life
- To explore Venus and Europa robotically requires spacecraft with science instruments that can survive extreme hot temperatures, extreme cold temperatures, and high-energy radiation

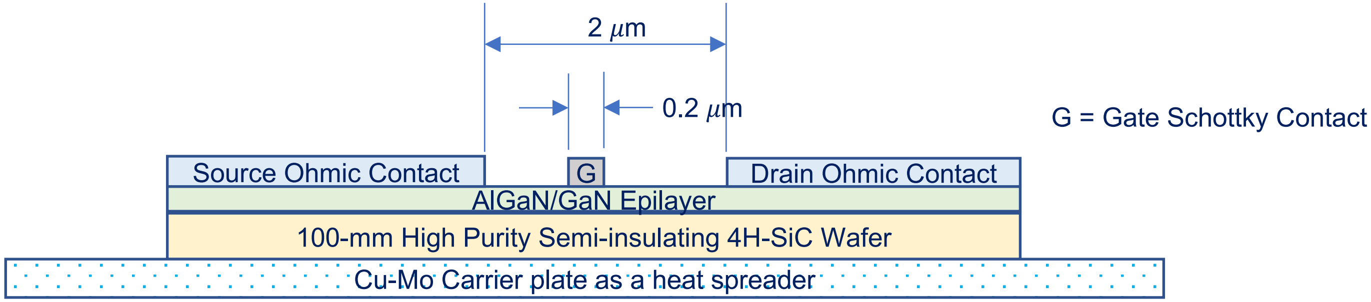
NASA Mission Requirements

- NASA's mission requirements and operating environments are diverse and completely different for each mission
- Especially true in the case of NASA's discovery and new frontier science missions (e.g., to Venus and Jupiter) and exploration missions (e.g., Artemis to Moon and Mars)
- Additionally, while operating in the harsh environment of space, the devices and systems for communications and data handling are subject to extreme temperature variations and high energy radiation
- Furthermore, they are required to have small size and low mass, consume small amount of DC power, operate with high efficiency, and perform reliably over extended periods

Relevant Material Properties — Wide Bandgap Semiconductors

- Literature search indicates that wide bandgap semiconductors such as SiC and GaN have unique material properties which enable them to operate in harsh environments

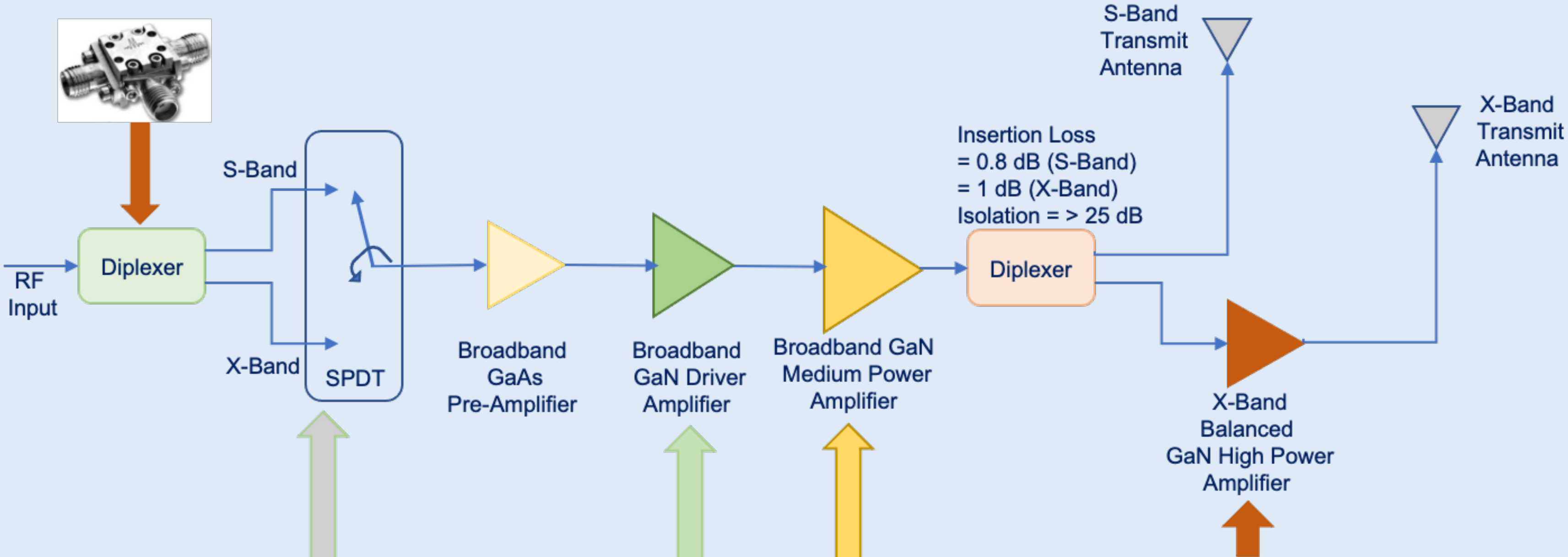
Material	**Mobility, μ_n, cm^2/V.s**	**Bandgap, E_g, eV**	**Relative Dielectric Constant, ε_r**	**Breakdown Voltage, E_b, 10^6 V/cm**	**Saturation Drift Velocity, V_{sat}, 10^6 cm/s**	**Thermal Conductivity, K, W/cm K**
Si	1350	1.1	11.8	0.3	10	1.5
GaAs	8500	1.42	13.1	0.4	10	0.43
4H-SiC	700	3.26✓	10	3.0✓	20	3.3 – 4.5✓
GaN	1200 (Bulk) 2000 (2DEG)✓	3.39✓	9.0	3.3✓	25✓	1.3



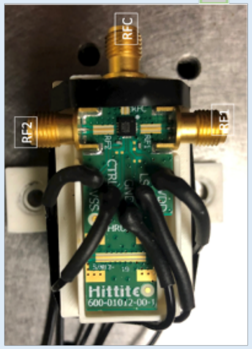
GaN for RF/Microwaves—Advantages

- Wide bandgap semiconductor material such as gallium nitride (GaN) has large bandgap, high electron saturation velocity, excellent thermal properties, and 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
  - Offer good linearity
  - Bestow high power added efficiency
  - Perform at elevated temperatures

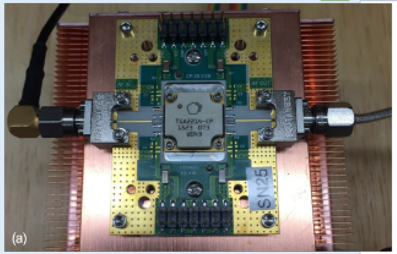
Reconfigurable GaN Based Fully Solid-State Microwave Power Module



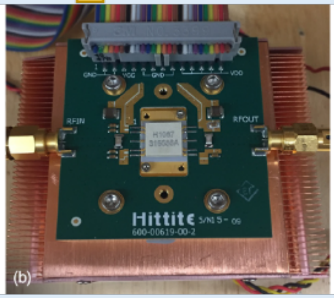
Insertion Loss
= 0.8 dB (S-Band)
= 1 dB (X-Band)
Isolation = > 25 dB



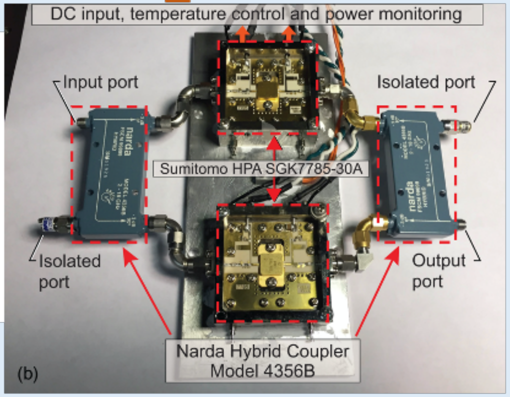
Insertion Loss
= 0.6 dB (S-Band)
= 1.4 dB (X-Band)



$P_{(Sat)}$ = 37 dBm
Gain = 20 dB
PAE = 25%

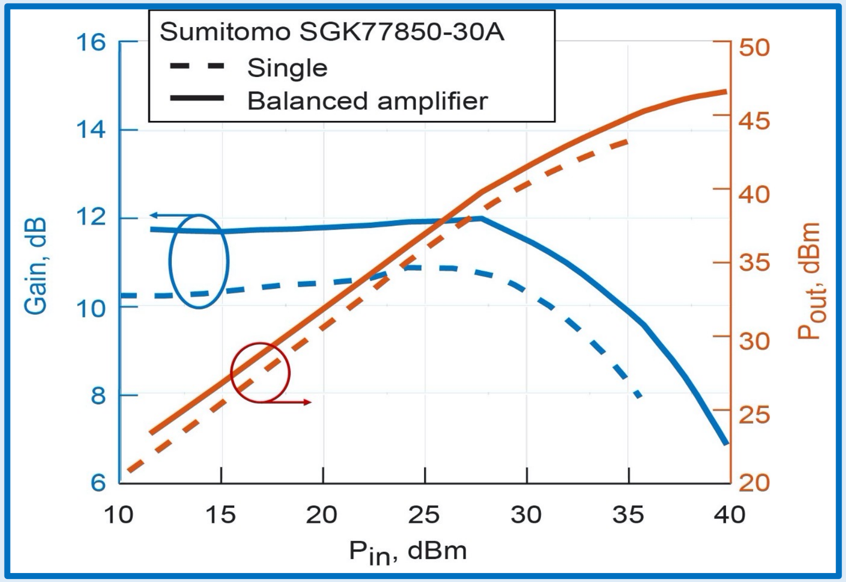


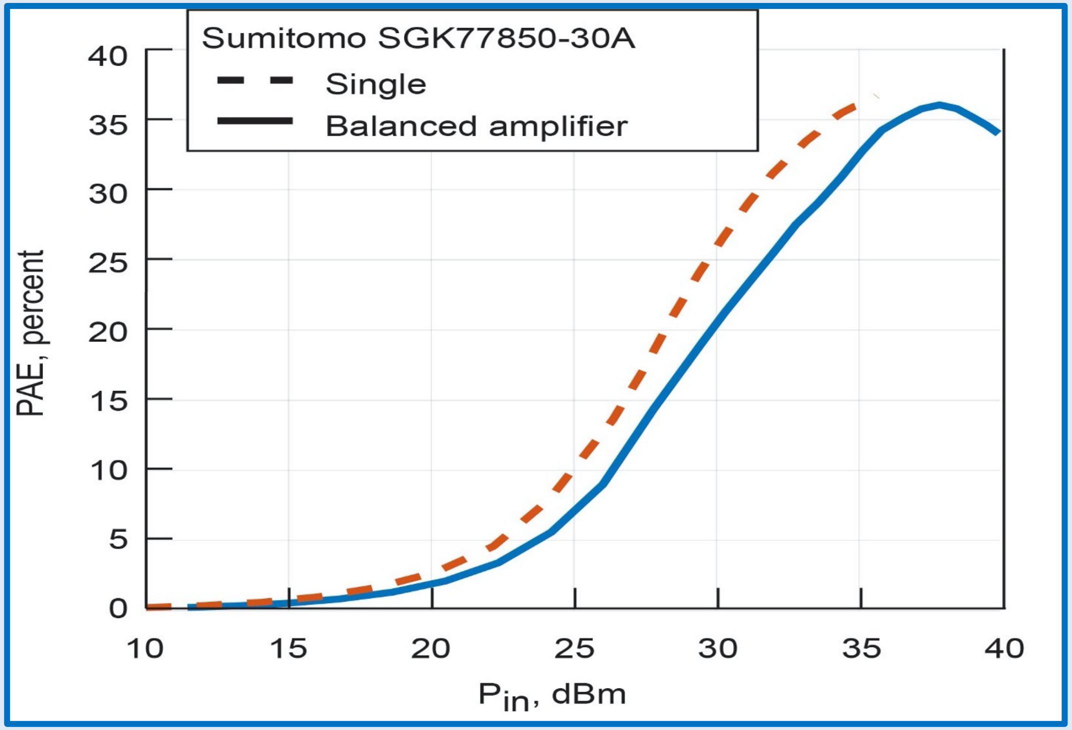
$P_{(Sat)}$ = 39.5 dBm
Gain = 8.8 dB
PAE = 27%



$P_{(Sat)}$ = 46.7 dBm
Gain = 6.8 dB
PAE = 34%

X-Band Balanced Amplifier Output Power, Gain & Power Added Efficiency



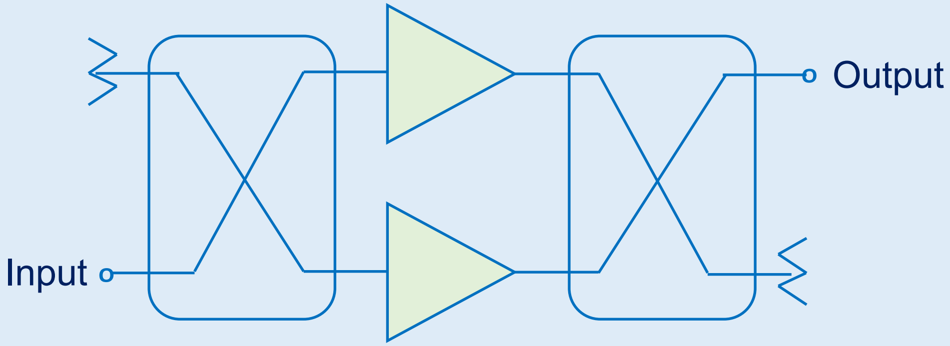


P-Band (420 - 450 MHz) GaN High Power Amplifier (HPA)

- Target Mission: BIOMASS
  - Sun-synchronous Low Earth Orbit
- BIOMASS Mission Objective:
  - Assess the worldwide spatial distribution of the forest biomass and to monitor its dynamics from space
- Other Applications:
  - Synthetic aperture radar (SAR) for imaging of subsurface features of Mars
  - P-band allows deeper ground penetration and subsurface imaging
- Main Instrument:
  - P-Band (UHF) (435 MHz) polarimetric synthetic aperture radar (SAR)

P-Band (420 - 450 MHz) GaN High Power Amplifier (HPA)

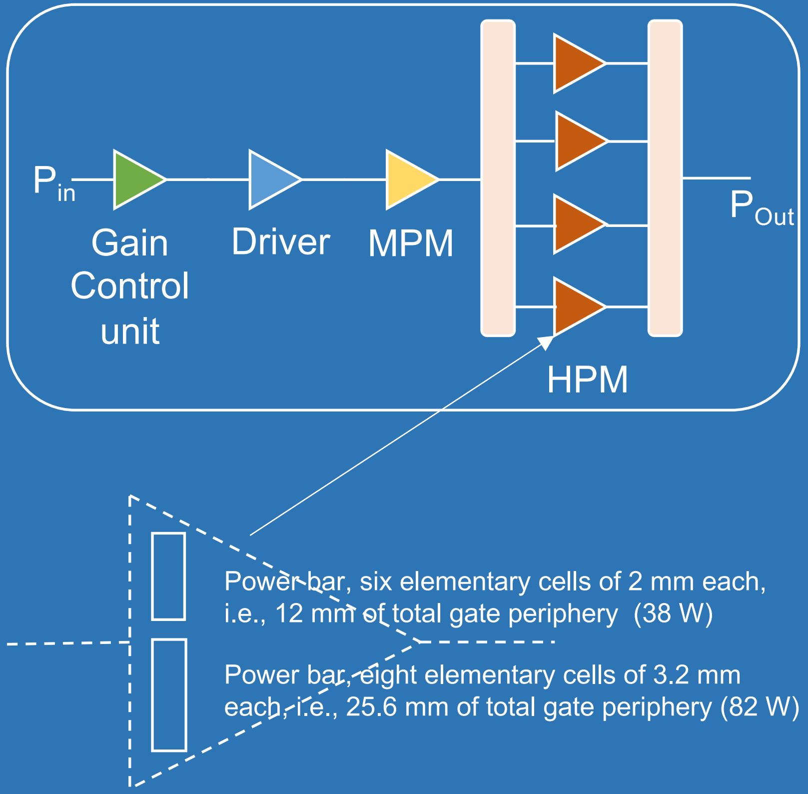
- Architecture of the HPA



- Device features:
    - 0.5 µm gate-length GaN HEMT on SiC
    - United Monolithic Semiconductor, 80W device (CHK080A)
- Amplifier performance:
    - Operating frequency = 435 MHz
    - V_{ds} = 40 V
    - Pulsed mode, 60 µs, 12% duty cycle
    - Output power = 180 W (across -15ºC to +55ºC)
    - Drain efficiency = 65%
    - Linear gain = 18 dB

L-Band GaN Solid State Power Amplifier (SSPA)

- Target Mission: 2^{nd} Generation Galileo Navigation System
    - 24 operational satellites, plus 6 in-orbit spares
- Transmission frequencies:
    - f1 = 1192±46 MHz, f2 = 1278±25 MHz, and f3 = 1575±25 MHz
- Device features:
    - 0.5 µm gate-length GaN HEMT on SiC
    - United Monolithic Semiconductor
    - Junction temp = 160ºC
    - Power density = 3W/mm
- Amplifier performance:
    - Operating frequency (GHz) = 1.55-1.6
    - V_{ds} (V) = 50 V
    - Output power (CW) (W) = 230 (300 @sat)
    - Overall Efficiency* (%) = 44
    - Gain (dB) = 65
    - Size (cm) = 30 x 24.5 x 52
    - Mass (kg) = 3.8



Power bar, six elementary cells of 2 mm each, i.e., 12 mm of total gate periphery (38 W)

Power bar, eight elementary cells of 3.2 mm each, i.e., 25.6 mm of total gate periphery (82 W)

*includes power supply unit and electronic power conditioner

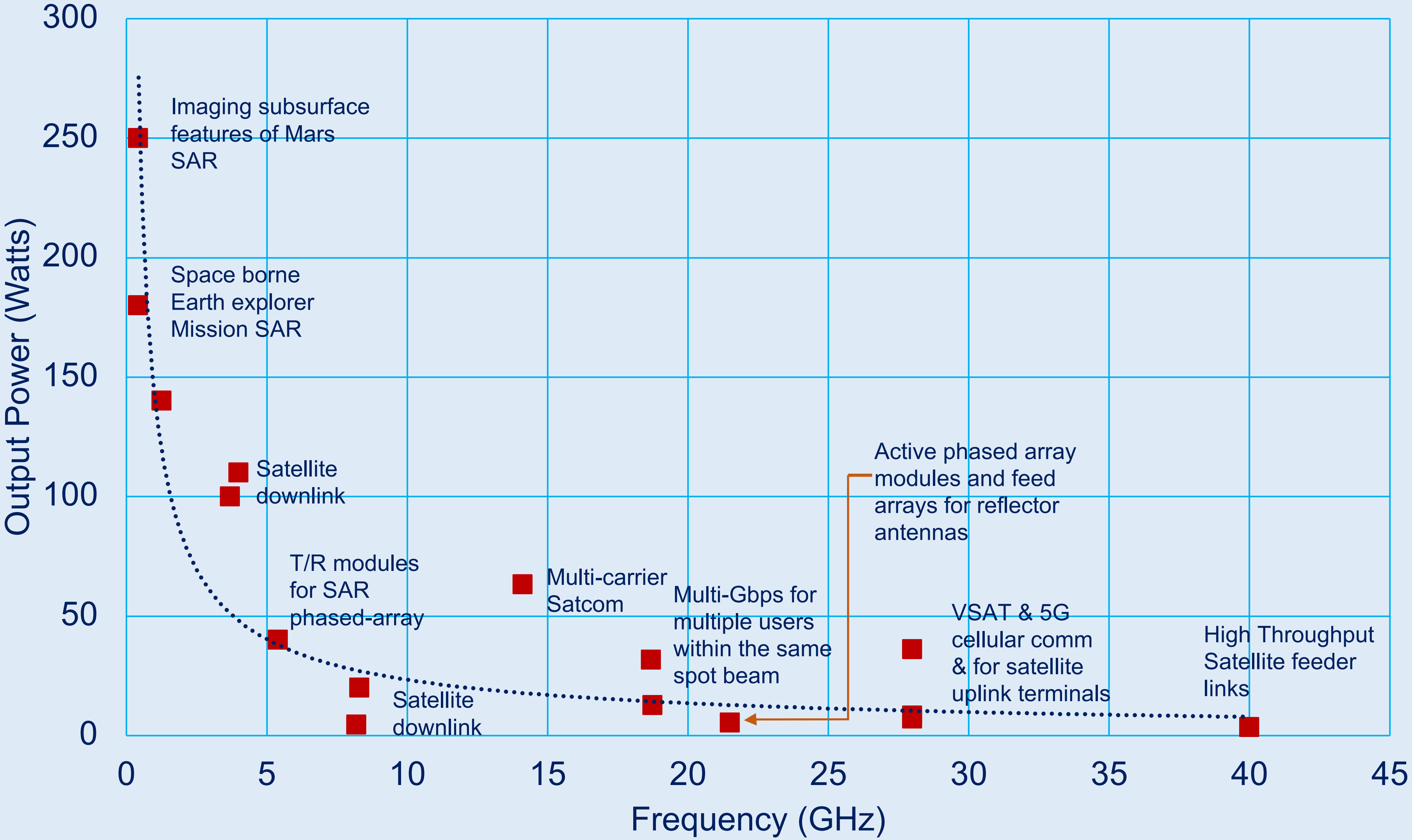
GaN Low Noise Amplifier (LNA)

- Space borne receiver front-end
- Advantages:
  - GaN LNA can handle high input power
  - Does not require a limiter consequently improves noise figure (NF)

Measured Results			
Parameter	C-band	Ku-band	Ka-band
Frequency (GHz)	6	14	28
Noise Figure (dB)	1.2	1.9	4.0
Gain (dB)	>21	>19.8	>18
P_{1dB} (dBm)	>28	>28	>12.5
Survivability Power at Input (dBm)	42	42	28

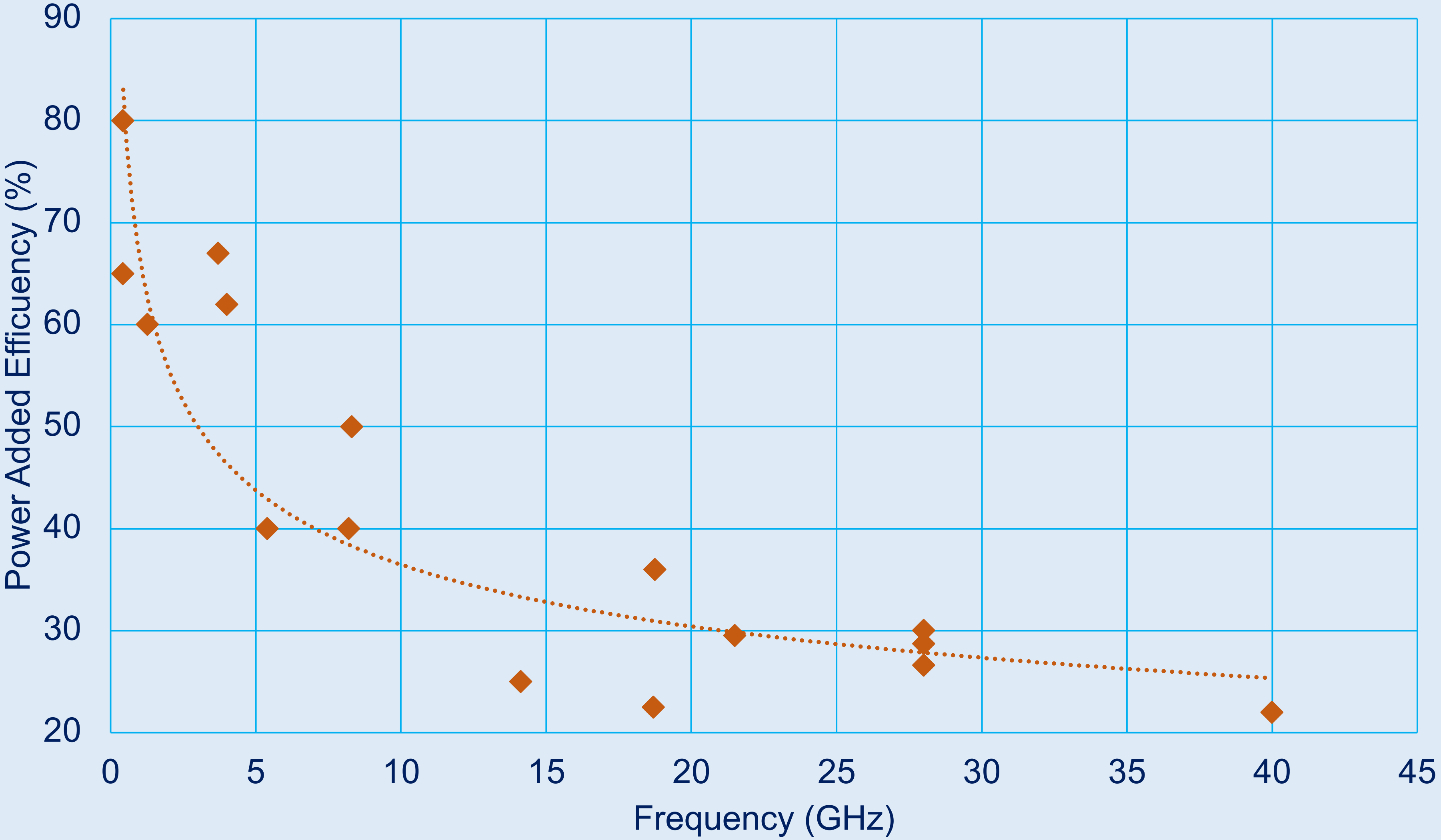
GaN High Power Amplifier Performance

(Output Power vs. Frequency)

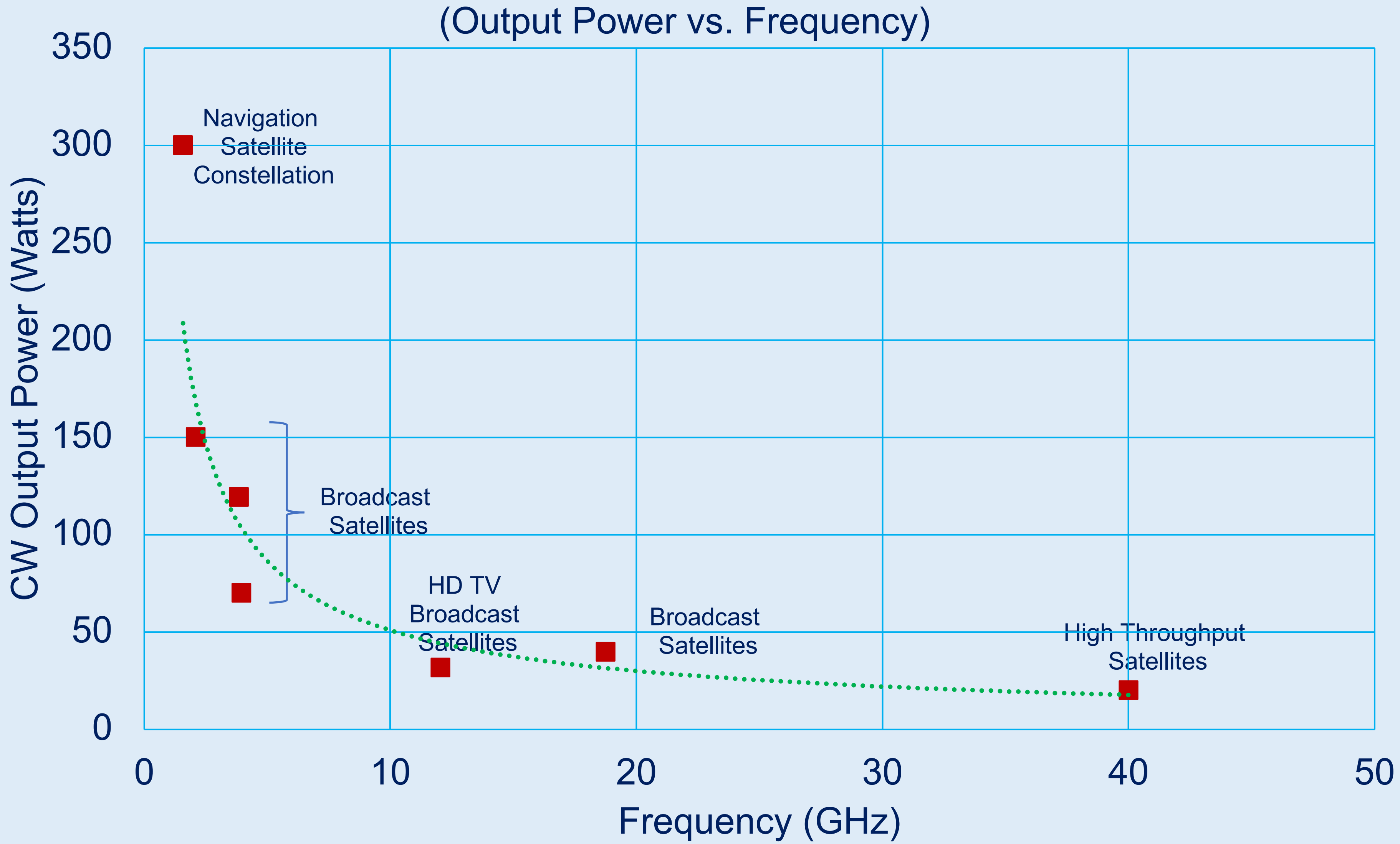


GaN High Power Amplifier Performance

(Power Added Efficiency vs. Frequency)



GaN Solid State Power Amplifier Performance



Conclusions & Discussions

- GaN HEMTS enable higher power density, higher efficiency amplifiers resulting in lighter, smaller, and more efficient RF/microwave systems in contrast with Si, SiGe, and GaAs based devices