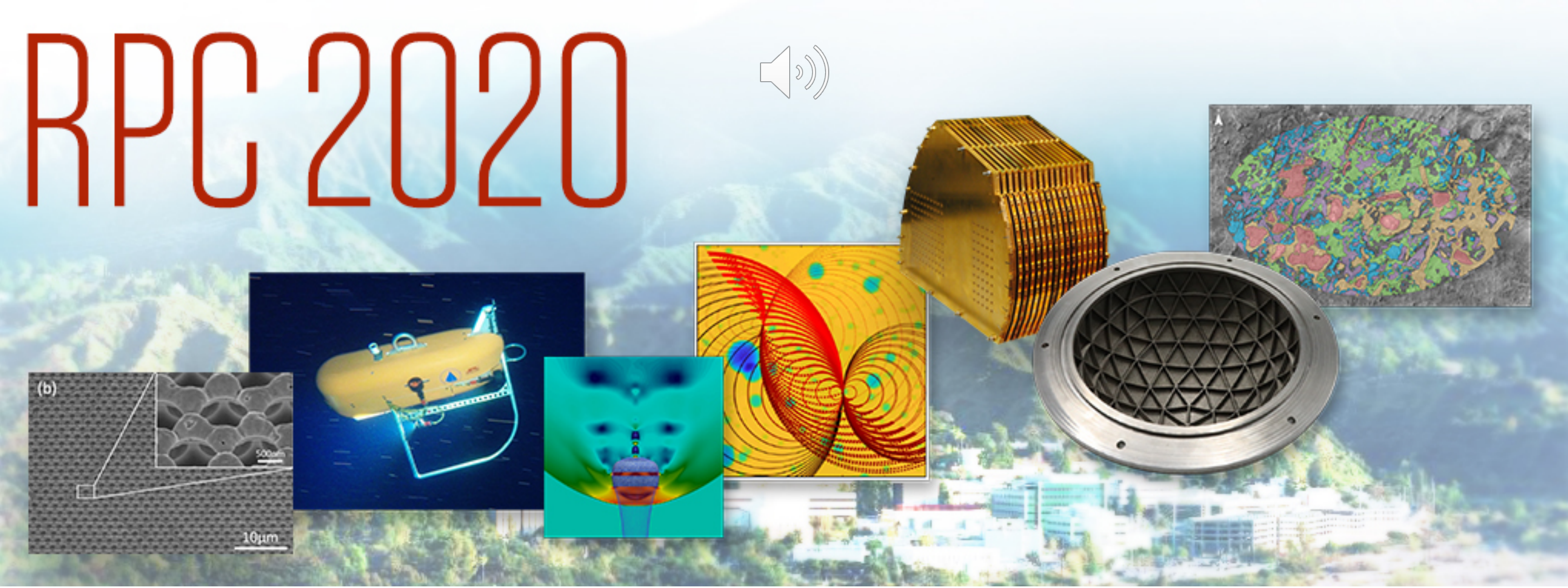


Virtual Research Presentation Conference

Ka-band GaN-based Solid-State Power Amplifier for Deep-Space Telecommunications

Principal Investigator: Michael Kobayashi (337)
Co-Is: S. Rahimizadeh (333), M. Taylor (333), S. Haque (337)
Program: Strategic Initiative

Assigned Presentation #RPC-283

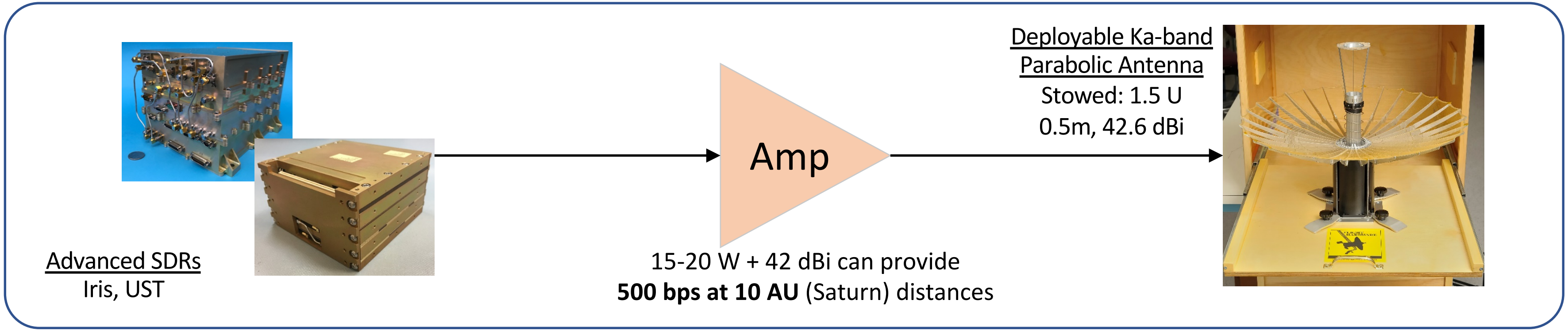
Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

Abstract

The objective of this research was to investigate the path towards achieving a highly efficient Ka-band (31.8 to 32.3 GHz) solid-state power amplifier for deep-space telecommunications applications. The goal of this 3-year task is to develop a **high-efficiency power amplifier that can provide approximately 500 bps of telemetry downlink to the DSN at a range of 10 Astronomical Units** in conjunction with the 42 dBi gain from the Ka-band Parabolic Deployable Antenna. The development of such a Ka-band SSPA fills the gap between various other investments in advanced software-defined radios (SDRs) and deployable antenna technologies.

The main objectives for Year-2 of this 3-year task was to **1)** complete the design of a high-efficiency monolithic GaN amplifier MMIC for a target fabrication start-date of January 2020, **2)** continue the investigation of an alternate discrete approach to providing impedance matching, and **3)** complete the optimization of the spatial power-combiner and fabricate it for test. 2020 has been a challenging year with the COVID-19 pandemic affecting various sectors, introducing large uncertainties for fabrication plans and delivery dates. Some course corrections were necessary as a result, but many goals were still met despite the disturbance.



Advanced SDRs
Iris, UST

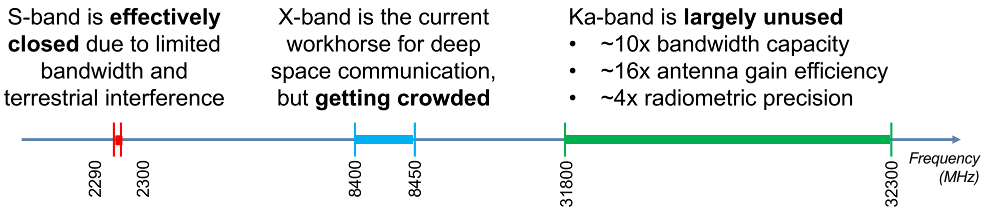
Deployable Ka-band
Parabolic Antenna
Stowed: 1.5 U
0.5m, 42.6 dBi

15-20 W + 42 dBi can provide
500 bps at 10 AU (Saturn) distances

Problem Description

1. Spectrum allocation for deep-space comm

- S-band is effectively closed due to limited bandwidth
- X-band is getting crowded as current workhorse
- Ka-band remains largely unused despite advantages



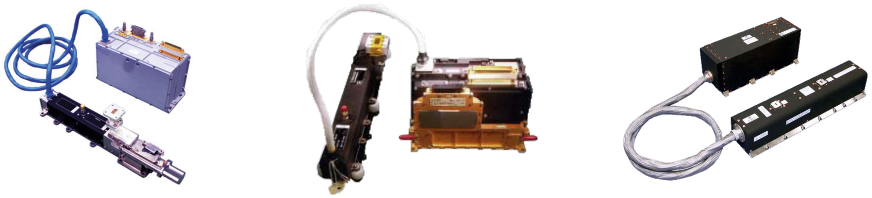
S-band is **effectively closed** due to limited bandwidth and terrestrial interference

X-band is the current workhorse for deep space communication, but **getting crowded**

Ka-band is **largely unused**
- ~10x bandwidth capacity
- ~16x antenna gain efficiency
- ~4x radiometric precision

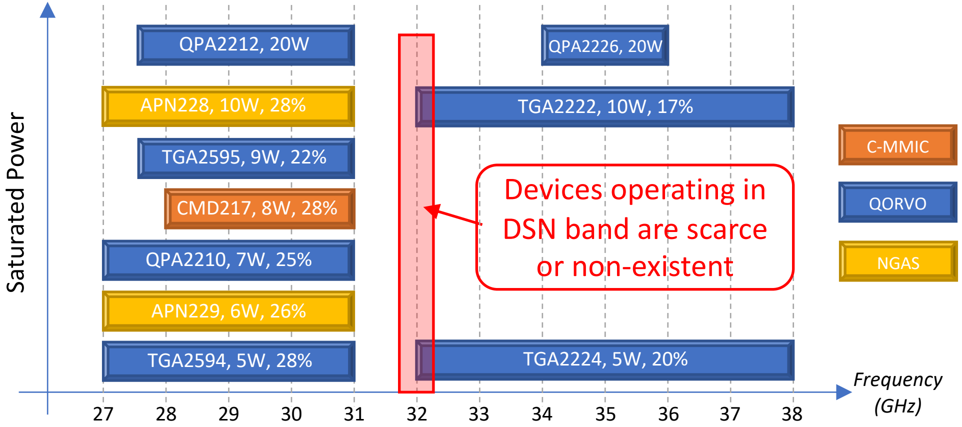
2. Disadvantages of vacuum-based amplifiers

- Mass/volume prohibitive on SmallSat platforms
- Requires extensive high-voltage expertise
- Sensitive to dynamic shock/vibration environments
- US manufacturing capability disappearing



3. No suitable commercial devices available today

- Vendors focus on wideband GaN devices
- Low efficiency < 30% to cover multi-GHz bandwidth
- Focus is NOT the DSN band (31.8-32.3 GHz)
  - 27-31 GHz: Satcom
  - 32-38 GHz: Radar, Terrestrial Comm, and EW



Devices operating in DSN band are scarce or non-existent

Research Presentation Conference 2020

Methodology and Results

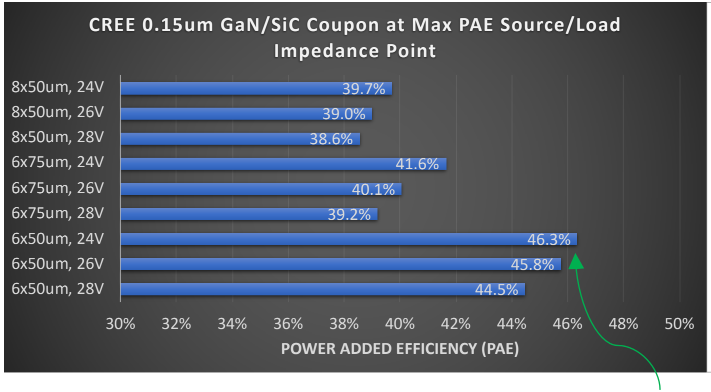
Monolithic GaN MMIC Approach

Develop harmonically-tuned GaN amplifier to optimize efficiency

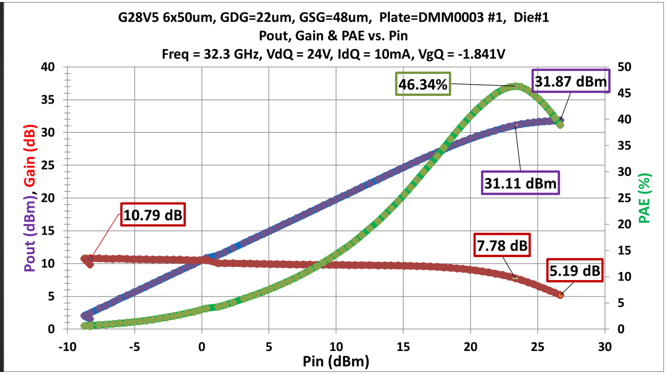
- Recent advances on GaN processes provide shorter gate length
- Reduced parasitic reactance → higher frequency response
- Selected CREE/Wolfspeed's 150-nm GaN/SiC process
    - Highest output power and maturity amongst competitor processes

Performed harmonic source-/load-pull characterization to determine optimum impedances for peak efficiency

Extremely High Gamma 10-67GHz Load-Pull Station



CREE 0.15um GaN/SiC Coupon at Max PAE Source/Load Impedance Point



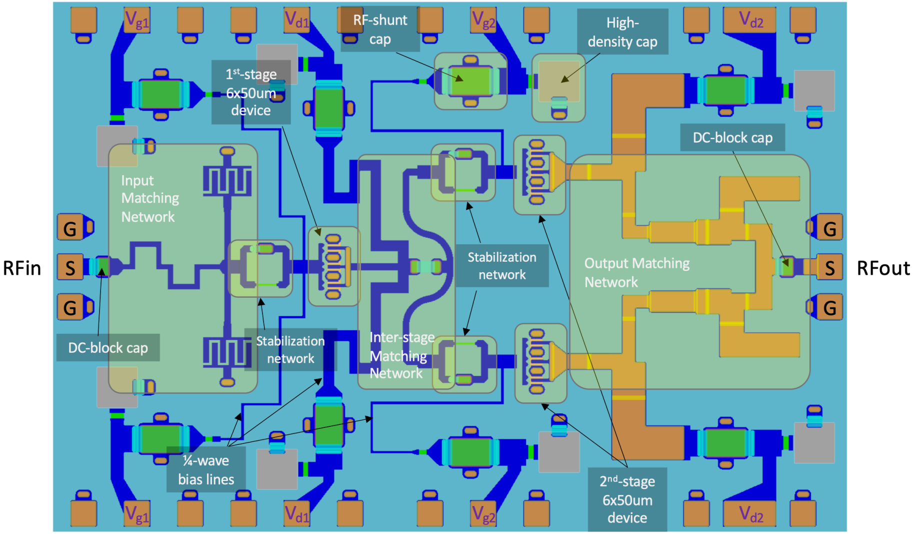
G28V5 6x50um, GDG=22um, GSG=48um, Plate=DMM0003 #1, Die#1
Pout, Gain & PAE vs. Pin
Freq = 32.3 GHz, VdQ = 24V, IdQ = 10mA, VgQ = -1.841V

Highest PAE of 46.3% measured at 24V bias

Methodology and Results

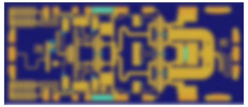
Monolithic GaN MMIC Approach

Specification	As Designed
Topology:	2-stage Harmonic-Tuned IMN & OMN
Frequency:	31.8 to 32.3 GHz
Pout:	2.6 W (~34.1 dBm)
PAE:	35-37%
X/Y Size:	2x3 mm
S11 / S22:	-22.5 dB / -14.9 dB
S21:	20.8 dB
Bias:	+24 V @ 135 mA
Psat:	2.8 W (34.5 dBm)



TGA2224

32 – 38 GHz 5 Watt GaN Amplifier

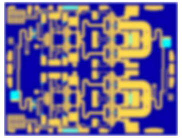


Key Features

- Frequency Range: 32 – 38 GHz
- P_{SAT} (P_{IN}=21 dBm): > 37 dBm
- PAE (P_{IN}=21 dBm): > 20 %
- Power Gain (P_{IN}=21 dBm): > 16 dB
- Small Signal Gain: > 25 dB
- Bias (pulsed): V_D = 26 V, I_{DQ} = 320 mA
- Bias (CW): V_D = 24 V, I_{DQ} = 320 mA
- Die Dimensions: 3.43 x 1.47 x 0.05 mm

TGA2222

32 – 38 GHz 10 Watt GaN Amplifier



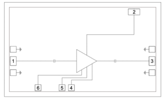
Key Features

- Frequency Range: 32 – 38 GHz
- P_{SAT} (P_{IN}=24 dBm): > 40 dBm
- PAE (P_{IN}=24 dBm): > 22 %
- Power Gain (P_{IN}=24 dBm): > 16 dB
- Small Signal Gain: > 25 dB
- Bias (pulsed): V_D = 26 V, I_{DQ} = 640 mA
- Bias (CW): V_D = 24 V, I_{DQ} = 640 mA
- Die Dimensions: 3.43 x 2.65 x 0.05 mm

CMD217

28-32 GHz GaN Power Amplifier

Functional Block Diagram



Parameter	Min	Typ	Max	Units
Frequency Range	28 - 32			GHz
Gain		20		dB
Input Return Loss		13		dB
Output Return Loss		15		dB
Output P1dB		36.7		dBm
Psat		39		dBm
Output IP3		41.5		dBm
Power Added Efficiency		32		%
Supply Current		580		mA

Significance of Result:

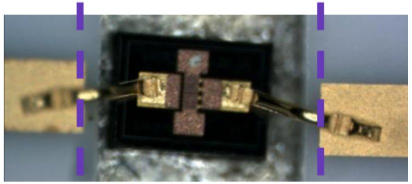
- **Best-in-class PAE** using CREE's 150-nm GaN/SiC process providing tuned performance for the DSN's 31.8-32.3 GHz Ka-band downlink frequency allocation
- Similar technique employed on other GaN processes (HRL, OMMIC, NGAS) could potentially yield even higher efficiencies with future maturity

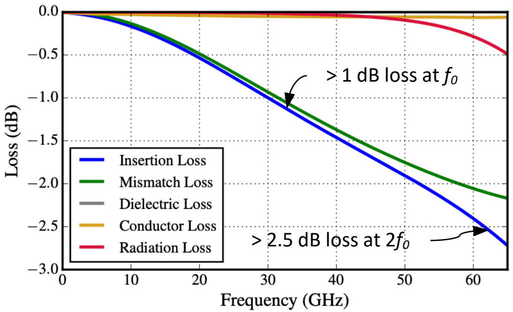
Methodology and Results

Effects of Losses at 32 GHz for a Hybrid Off-Chip Matching Approach

Develop harmonically-tuned GaN amplifier using high-Q off-chip elements

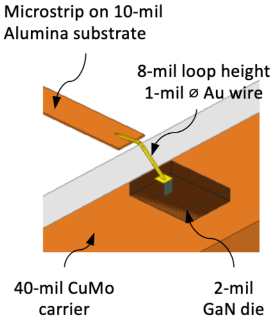
- Bond-wire interconnect from drain of GaN transistor to off-chip matching network
- Microstrip resonator matching network on standard Alumina substrate
- Custom-tuned single-layer capacitor for output DC block

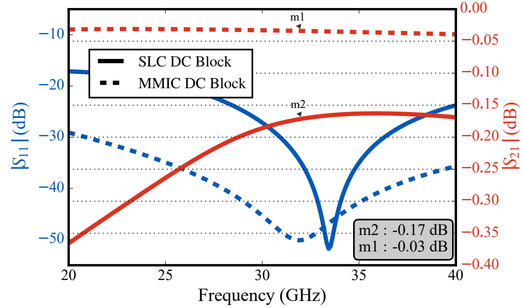


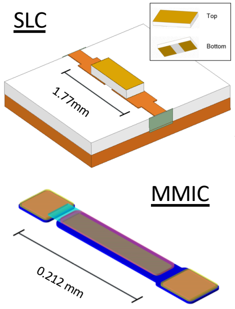


> 1 dB loss at f_0

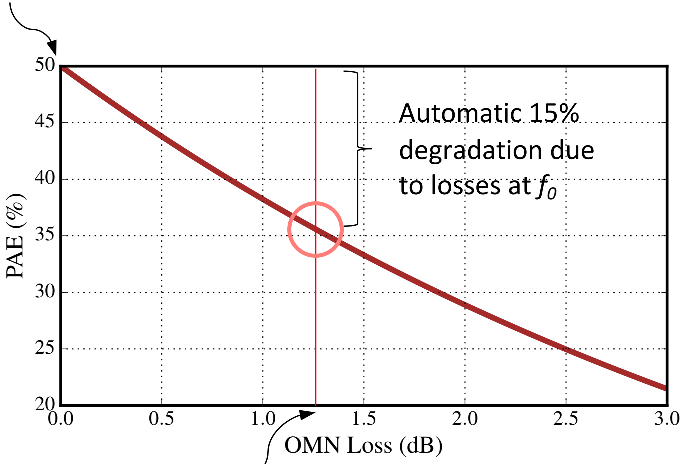
> 2.5 dB loss at $2f_0$







Assume device provides 50% efficiency using loss-less output matching network

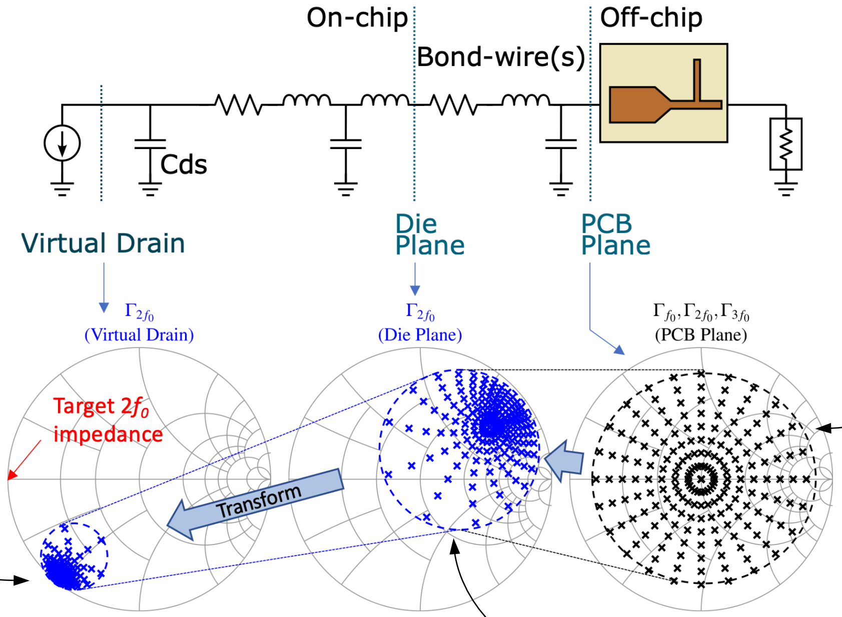


Automatic 15% degradation due to losses at f_0

Loss at f_0 for bond wire & DC block cap is already ~ 1.2 dB

Methodology and Results

Effects of 2^{nd}-harmonic Losses at 64 GHz for a Hybrid Off-Chip Matching Approach



1) Assume arbitrary impedance at 64 GHz is presented by the off-chip matching network

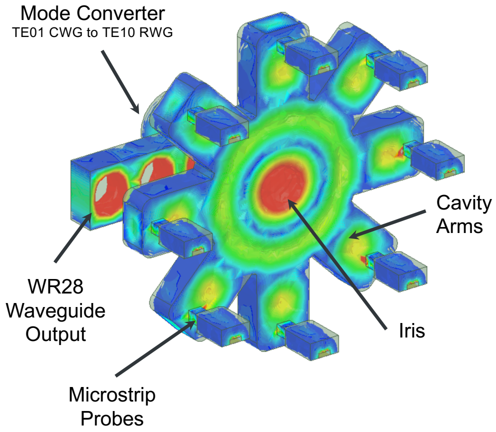
2) Bond-wire resistive losses contract overall area and reactance presents phase shift to impedances

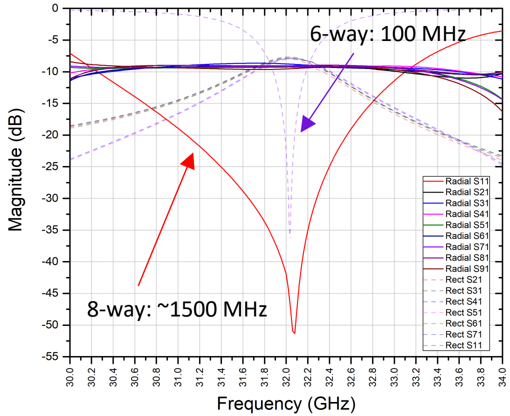
3) Further contraction of impedances due to larger losses on GaN substrate, and rotations presented by device parasitic (e.g.: Cds)

This illustrates that there is no passive impedance that can be realized in an off-chip matching network that will result in the harmonic impedances necessary for high-efficiency operation.

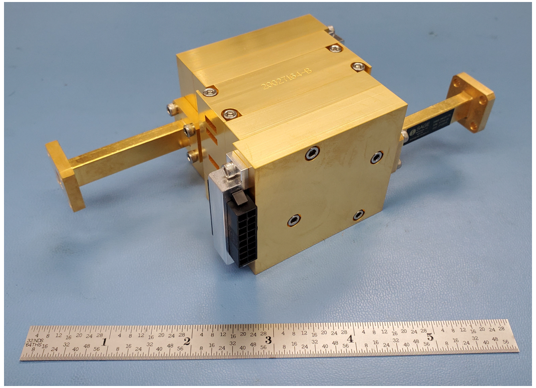
Methodology and Results

Spatial Power Combiner for Higher Output Power





Fabricated/Assembled Spatial Power Combiner



- Spatial combiners use waveguide modes to power combine the amplified EM waves for high output power
- Compared to the 6-way rectangular design from Year-1, a novel 8-way radial design shows significant bandwidth improvement of over 10x with low loss of approximately 0.6 dB
- Coupled with the 2.5-Watt 37%-efficient MMIC, the expected combined RF output power is 18 Watts with an overall efficiency of 32%
- Link budget using a 42-dBi antenna to a DSN station with convolutional coding shows maximum downlink rate of 700 bps can be supported with 3 dB of margin at 10 AU

Conclusions

- Off-chip hybrid matching for high-efficiency operation at Ka-band is not feasible, due to large losses and impedance transformations introduced by bond-wire interconnects, DC blocking capacitors, and intrinsic device parasitic of GaN transistors
- A highly-efficient (35-37% PAE) 2.5-Watt MMIC power amplifier using CREE's V5 150-nm GaN/SiC process was designed for operation in the DSN 31.8-32.3 GHz frequency band, providing significant improvement against commercially-available devices that are typically < 20% PAE
- A novel 8-way radial spatial power combiner was designed to provide low-loss power combination for the DSN 31.8-32.3 GHz frequency band
- An 18-Watt RF output, 32% overall efficiency SSPA can be expected from the combination of the 2.5-W MMIC and 8-way spatial combiner designed in this study.
- The 18-Watt SSPA coupled with a 42-dBi antenna is expected to provide over 500 bps of telemetry downlink to the DSN from a range of 10 AU (Saturn)