High Voltage RF GaN Technology for Spaceborne UHF Synthetic Aperture Radar Applications

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IEEE WAD Phoenix Chapter
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9-15-2016
OUTLINE

1. Objectives of UHF Spaceborne SAR
2. High Efficiency Power Amplifiers
3. TCAD Design of High Voltage RF GaN
4. Measured DC & RF Results
5. Reliability Data
6. Conclusions & Further Work
UHF Spaceborne SAR

**P-band (420-450 MHz):** long EM waves penetrate foliage and ground, ideal for subsurface imaging

BIOMASS (ESA)

AirMOSS (NASA)

**Objective:** Multi-Mission Subsurface Imaging Radar (MMSIR, NASA)
Space SAR **constrains:**

- Prime Power Budget
- Antenna / Array **Size**
- System **Weight**
- Thermal Management
- Radiation Effects
- System **Cost**

**Reference:** Leopold Cantafio

*Space-Based Radar Systems and Technology,* chapter 22 in Skolnik “Radar Handbook”

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Space SAR **enablers:**

- High Efficiency Power Amplifiers
- Lightweight GaN T/R Modules
- Large deployable antenna
Example:
Venus – Magellan Mission

Surface of Venus seen by SAR imaging
Courtesy of NASA / JPL

Frequency 2.385 GHz (S-band)
Peak Power 325 watts
Antenna Diameter 3.7 m
Pulse Length 26.5 µs
PRF 4400 - 5800 Hz
Range ~150 m
Cross Range ~150 m
Example: SMAP – Soil Moisture Active Passive Mission

Frequency 1215-1280 MHz (L-band)
Peak Power 500W
Antenna Diameter 6 m
Pulse Length 15 µs - PRF 2850 Hz

The L-band frequency enables observations of soil moisture through moderate vegetation cover, independent of cloud cover, at night or day.

Courtesy of NASA / JPL

http://smap.jpl.nasa.gov/
### P-Band Example: AirMOSS

**Airborne Microwave Observatory of Subcanopy and Subsurface**

**AirMOSS**
- Platform altitude: 12 km above terrain
- Pulse width: 40 us
- PRF (fast): 1200 Hz
- **Center frequency**: 420 MHz
- **Transmit Power**: 1995W

**Mission Parameters**

Airborne SAR to Measure Root Zone Soil Moisture

![AirMOSS Mission Parameters](http://airmoss.jpl.nasa.gov/)

Courtesy of NASA / JPL
P-Band Example: BIOMASS (ESA)

<table>
<thead>
<tr>
<th>BIOMASS</th>
<th>Mission Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>&gt;10 m diameter</td>
</tr>
<tr>
<td>Pulse width</td>
<td>up to 88 us</td>
</tr>
<tr>
<td>PRF (fast)</td>
<td>1700 Hz</td>
</tr>
<tr>
<td>Frequency</td>
<td>432 - 438 MHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>200W from 2x 100+ W modules</td>
</tr>
</tbody>
</table>

Main Objective: (above) ground-cover vegetation
Why P-Band SAR?

• Signal can penetrate deeper into the soil and or foliage for detection of underground or buried structures.

• Already used by NASA/JPL on AirMOSS program (2 kW peak power) to gather data of root zone soil moisture.

• Applicable to subsurface imaging in planetary exploration.

• SBIR Phase I and II Awards to Integra Technologies, Inc. to develop 1 kW RF power module with > 70% efficiency in P-band program sponsored by NASA/JPL

S1.02-9058 - A High Efficiency 1kWatt GaN amplifier for P-Band pulsed applications
NASA SBIR/STTR Technologies
S1.02-9058 – A High Efficiency 1kWatt amplifier for P-Band pulsed Applications

PI: James Custer
Integra Technologies, Inc. – El Segundo, CA

Identification and Significance of Innovation
The proposed innovation is a high efficiency 1kW two stage power amplifier for P-Band RADAR applications. The amplifier will utilize GaN HEMT device technology specifically tailored for high peak power and high efficiency. Amplifier will require two stages of gain to achieve greater than 40dB of gain at P-Band. The transistors will be assembled on high thermally conductive carriers and integrated with a PCBA for power combining, impedance matching, and bias control.

The RF impedance matching circuits will include harmonic tuning to optimize efficiency by creating a switch mode design that will target the second and third harmonics for optimized efficiency (>80%). The amplifier PCBA materials, components, and layout topology will be selected for reliability under high pulsed power conditions, including thermal considerations, breakdown under low pressure environments, including Multiplication effects, and high mechanical stresses.

Expected TRL Range at the end of Contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan
GaN HEMT die for High Power and High Efficiency P-Band Operation: Investigate new GaN transistor designs and die topologies that enable improved operation at P-Band. An important aspect will be to develop high voltage devices that can simplify RF circuit design and improve RF circuit performance, with respect to high efficiency.

High efficiency Switch Mode amplification: Develop inverse Class F or Class E Switch Mode amplifier circuit topology for optimum fundamental and harmonic optimum load impedances. Devise circuit elements that allow operation under high peak power conditions.

Space qualify-able amplifier design: Develop a multi-stage RF amplifier with design elements that enable reliable operation in a space environment. Utilize passive circuit techniques to enable optimized harmonic tuning. Investigate amplifier module design for good thermal management and low mass. Select a PCB transmission line topology to mitigate Multiplication effects. Select components and material that are qualified for space operation.

The research project will achieve the technical objectives by completing the following milestones:
- Design a new GaN Transistor device for optimum P-Band Performance
- Design a pallet amplifier to achieve the Power and Efficiency Goals

NASA Applications
A target application for this pulsed power amplifier can be SAR imaging of surface features for Mars, other non-terrestrial objects, or the terrestrial surface. An airborne test bed system for Biomass estimation (Airmoss) is operation using P-Band SAR that is the precursor to space instruments. Future interplanetary missions outfitted with the Multi-Mission Subsurface Imaging Radar (MM-SIR) could use this amplifier technology.

Non-NASA Applications
The International Telecommunication Union (ITU) and the US government have specified the UHF radar band from 420-450MHz primarily for radiolocation. One popular non-government use would be for wind profiler radars. Other nongovernment customers may have future interest if the band is opened to telecommunication and land/mobile public safety systems.

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NON-PROPRIETARY DATA
NASA-MMSIR objectives are:

1. High peak Power (1 kW) needed to have good enough SNR in strongly attenuated EM waves in lossy material (wet / moisture in soil)

2. With 1 kW peak Power need High Efficiency to fit in aircraft prime power budget; high efficiency also reduces waste heat for simpler thermal management subsystem & overall lower mission costs

3. High Power is also suitable with smaller antenna as it is hard to maneuver spacecraft with too large antenna in interplanetary mission

GaN technology is definitely an enabler for high efficiency power amplifiers and new mission concepts
NASA-MMSIR Objective Summary:

- Peak Power: 1 kW
- Frequency band: 420 - 450 MHz
- PAE: > 70% PAE
- Gain: > 40dB
- Signal: 100us, 10%
- Weight: < 500 gr.
HEPA Design Strategy

Harmonic Tuning techniques (class E, F, inverse F)

1. GaN device requires: $B V_{DSS} \geq 3 \times V_{DD}$

2. Low $C_{DS}$ or it is hard to tune harmonics when $Z$ is too low

$$Z_C = \frac{1}{j 2 \pi f C_{DS}}$$

- GaN fits the bill:
  - Low $C_{DS}$ parasitic capacitances & high power density
  - Wide bandgap material = radiation tolerant
SBIR Phase I - approach

• Designed PA with a 24mm GaN device made by Integra Technologies, Inc. operated at 50 V

• Achieved 160 W across 420-450 MHz band and demonstrated > 80% drain efficiency

• HEPA design based on combination of class E and inverse class F
Phase I
Measured Results

SBIR Phase I - Results

24mm Die Measured Parameter

C_{DS} 12pF
R_{DS} 12.5 \Omega

\[
Z_C = \frac{1}{j 2 \pi f C_{DS}} = -j 29.5 \Omega
\]

\[
R_{DS(\text{inv } F)} = \frac{\pi}{2} R_{DS(\text{class } B)} = \frac{\pi}{2} \frac{V_{DD}^2}{P_{RF}}
\]

\[
R_{DS(\text{inv } F)} = \frac{\pi}{2} \frac{(50V)^2}{2 \cdot 160W} = 12.3 \Omega
\]

Phase I - Conclusions

1 kW output power met with 8x 160 W devices

However:

\[ C_{DS} = 8 \times 12 \text{ pF} = 96 \text{ pF} \]

\[ Z_C = \frac{1}{j 2 \pi f C_{DS}} = - j 3.7 \Omega \]

\[ R_{DS(\text{inv F})} = \frac{\pi}{2} R_{DS(\text{class B})} = \frac{\pi}{2} \frac{V_{DD}^2}{2 P_{RF}} = \frac{\pi}{2} \frac{(50V)^2}{2 \times 1000W} = 2 \Omega \]

- Load impedance gets low; harder to optimize harmonic terminations for drain efficiency >= 80%
- Used TCAD to explore high voltage GaN transistors optimized for RF amplifiers at 75 V and 100 V bias.
Benefits of 100 V RF Devices

\[ P_{RF} = 1000 \text{ W} \]

\[ R_{DS(\text{inv } F)} = \frac{\pi}{2} \frac{V_{DD}^2}{2 \cdot P_{RF}} \]

\[ V_{DD} = 50 \text{ V} \quad \rightarrow \quad R_{DS} = 2 \ \Omega \quad 25x \text{ to } 50 \ \Omega \]

\[ V_{DD} = 75 \text{ V} \quad \rightarrow \quad R_{DS} = 4.4 \ \Omega \quad 11x \text{ to } 50 \ \Omega \]

\[ V_{DD} = 100 \text{ V} \quad \rightarrow \quad R_{DS} = 7.9 \ \Omega \quad 6x \text{ to } 50 \ \Omega \]
Benefits of 100 V RF Devices

\[ P_{RF} = \frac{1}{4} (V_{DD} - V_{Knee}) \cdot IDS_{MAX} \]

High Voltage increases Power Density (W/mm) and reduces gate periphery \( W_G \) (and \( C_{DS}, C_{GS}, C_{GD} \)) for a given output power \( P_{RF} \).

\[ 2x V_{DD} \text{ requires } \frac{1}{2} IDS_{MAX} \text{ (or gate periphery } W_G) \text{ for same } P_{RF \text{.}} \]

DANGER

\[ \eta_B = \frac{\pi}{4} \left( 1 - \frac{V_{Knee}}{V_{DD}} \right) \]

Longer \( L_{GD} \) for higher \( V_{DD} \) results in higher \( RDS_{ON} \) and \( C_{DS} \), but \( C_{DG} \) decreases.

\[ 2x V_{DD} \text{ does NOT reduce efficiency as long as drift region does NOT increase } V_{Knee} \text{ by } 2x \]
TCAD Simulations

TCAD simulations of Integra’s 50 V baseline GaN process

$C_{GS} \approx 2 \text{ pF/mm}$

$BV_{DSS} \approx 135 \text{ V}$
TCAD Design of HV RF GaN

$BV_{DSS} > 250 \text{ V}$

TCAD simulations of Integra’s 100 V GaN process

$C_{DS} \approx 0.5 \text{ pF/mm}$

$C_{DG} \approx 0.05 \text{ pF/mm}$
Risk Factor with HV RF GaN

- Higher $BV_{DSS}$ is typically achieved with longer gate-drain extension $L_{GD}$

- Longer $L_{GD}$ leads to higher on-resistance $RDS_{ON}$ which translates to higher knee voltage $V_{Knee}$ and higher $C_{DS}$

- Increased $V_{Knee}$ negatively impacts maximum efficiency at $P_{SAT}$ which we are trying to increase by harmonic tuning techniques

- Therefore need higher $BV_{DSS}$ keeping $RDS_{ON}$ and $C_{DS}$ small
SBIR Phase II - approach

1. Design and build new GaN RF device operating at 75 V (design 1) and 100 V (design 2)

2. Target single chip for 250 W across 420-450 MHz band and demonstrate >80% drain efficiency

3. Use 2x 250 W = 500 W in a hermetic package

4. Design 1 kW HEPA module by combining 2x 500 W devices
Measured DC Data

Analyzed GaN wafers with different Fe profile in buffer layer; C is harder to control

Data show gate-drain spacing is larger parameter to control $\text{BV}_{\text{DSS}}$ but $\text{BV}_{\text{DSS}}$ also sensitive to Fe in buffer design and gate length
75 V 250 W device assembly

- 21 mm GaN transistor
- Series chip resistor
- Metal substrates & Bond Wires / Inductors needed to achieve high enough inductance for P-band frequencies
- MNM capacitor
The shunt caps on the input are for input impedance matching at \( f_0 \) only. The location of the shunt caps on the wide bias line sets the 2\(^{nd}\) and 3\(^{rd}\) harmonic impedance points for high efficiency. The shunt caps on the output are primarily for \( f_0 \) matching.

**Switch-Mode Circuit Design**

50 \( \Omega \) transmission lines
Measured RF Data

\( P_{\text{SAT}} \) vs. freq. at \( P_{\text{IN}} = 2 \) W

All four devices yield about the same output power of \(~250\) W

0.5\( \mu \)m versus 1\( \mu \)m yields \(~3\) dB higher gain; 100 V devices have 2-3 dB higher gain than 75 V

Measured RF Data

Drain Eff. vs. freq. at 250 W

100 V devices have ~ 5% drain efficiency points lower than 75 V

DROOP vs. freq. at 250 W

100 V devices have worse pulse droop than 75 V devices, most likely due to the lower efficiency they achieve.
Impedance of harmonics

Measured Impedances reflect an harmonic tuning that is a combination of Class E, F and inverse F amplifier mode of operation.

<table>
<thead>
<tr>
<th></th>
<th>Class E</th>
<th>F</th>
<th>F⁻¹</th>
<th>75V TF</th>
<th>100V TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₀</td>
<td>1 + j 0.725</td>
<td>1</td>
<td>1</td>
<td>1 + j 0.15</td>
<td>1 + j 0.19</td>
</tr>
<tr>
<td>2 F₀</td>
<td>- j 1.785</td>
<td>0</td>
<td>∞</td>
<td>0.11 - j 1.05</td>
<td>0.06 - j 0.51</td>
</tr>
<tr>
<td>3 F₀</td>
<td>- j 1.19</td>
<td>∞</td>
<td>0</td>
<td>0.01 - j 0.42</td>
<td>0.03 - j 0.19</td>
</tr>
</tbody>
</table>

C_DS = 10.5 pF - device 75 V
C_DS = 7.5 pF - device 100 V
C_DS ≈ 0.5 pF/mm
1um devices have lower spurs than the ones with 0.5um gate length which makes combining multiple chips for higher power easier in the future.
Select Best Design

- 75 V devices had better efficiency than the 100V ones.
- 1um devices had lower spurs and better stability than the 0.5um transistors under mismatch, important when combining two chips in the package for 500 W.
- Therefore, the 75 V design with 1um gate length was chosen to design and build the 1 kW pallet.
500 W GaN Device

2x 21mm 75 V dice

<table>
<thead>
<tr>
<th>Freq</th>
<th>Class E</th>
<th>F</th>
<th>F⁻¹</th>
<th>Normal. Z</th>
<th>Measured Z [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1+j0.725</td>
<td>1</td>
<td>1</td>
<td>1+j0.215</td>
<td>8.71+j1.87</td>
</tr>
<tr>
<td>f₀</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2f₀</td>
<td>-j1.785</td>
<td>0</td>
<td></td>
<td>0.051-j1.166</td>
<td>0.44-j10.16</td>
</tr>
<tr>
<td>3f₀</td>
<td>-j1.19</td>
<td>∞</td>
<td>0</td>
<td>0.006-j0.057</td>
<td>0.05-j0.495</td>
</tr>
</tbody>
</table>

Freq Class E F F⁻¹
4 GaN chips = 84mm

Amplifier features: 1 kW, 42 dB, 75% drain bias sequencer, TX mute, unconditional stable

0.020” thick RO4350 for multipaction only 280g & 17cm x 9cm x 3.1cm

VISIT US at PAWR-2017 for more info

Reliability

Need to prove high voltage RF GaN is reliable enough for deployment in space!

GaN is a wide-bandgap material

28V & 50V AlGaN/GaN HEMT technology from a few manufacturers is already space-qualified

Expectation is:
high voltage RF GaN is also radiation-hard and can be space-qualified!

Here we address:
1) output power stability (RF burn-in tests on 100 V devices taken at 125 V)
2) junction temperature $T_J$ (IR measurements & modeling)
3) Load line measurements
RF Burn-in

Epi with higher Fe content results in less degradation

Peak $T_J$ temperature during 1ms 10% pulse is 155 °C

IR measured data on 500W 2-chip 42mm device with 85 °C case temperature
Thermal Modeling

CPC flange
40mil thickness
$K_{TH} = 220 \text{ W/m} \cdot \text{°K}$

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness [µm]</th>
<th>Area [mil²]</th>
<th>$R_{TH}$ [°K/W] $T_{case} = 26$ °C</th>
<th>$R_{TH}$ [°K/W] $T_{case} = 80$ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN epi</td>
<td>2</td>
<td>152 x 40</td>
<td>0.139</td>
<td>0.147</td>
</tr>
<tr>
<td>SiC substr.</td>
<td>75</td>
<td>152 x 40</td>
<td>0.575</td>
<td>0.694</td>
</tr>
<tr>
<td>AuSn solder</td>
<td>25</td>
<td>152 x 40</td>
<td>0.112</td>
<td>0.112</td>
</tr>
<tr>
<td>CPC Pkg.</td>
<td>1016</td>
<td>152 x 40</td>
<td>1.178</td>
<td>1.178</td>
</tr>
<tr>
<td>Total $R_{TH}$</td>
<td></td>
<td></td>
<td>2.003</td>
<td>2.131</td>
</tr>
</tbody>
</table>


flange $R_{TH} = \frac{55.3}{100}$% of total
Thermal Model Calibration

Signal = 1ms, 10%

Measured & Simulated Data of 500 W 75 V device with 85 °C case temperature for model calibration – T_J = 155 °C
T\textsubscript{J} in operating conditions

Simulated Data of 500 W 75 V device with 85 °C case temperature for shorter pulse width

\textbf{Peak} T\textsubscript{J} temperature during 300\textmu s 10\% pulse is 128 °C

Simulated Data of 500 W 75 V device with 30 °C case temperature for shorter pulse width

\textbf{Peak} T\textsubscript{J} temperature during 300\textmu s 10\% pulse is 66 °C

T\textsubscript{J} < 150 °C during operation = good reliability
**T_J in RF Burn-in Tests at 125 V**

Simulated Data of 300 W 1-chip 15mm device with 80 °C case temperature for shorter pulse width at 125V

Peak T_J temperature during 100µs 10% pulse is 150 °C

Simulated Data of 350 W 1-chip 15mm device with 26 °C case temperature for shorter pulse width at 125V

Peak T_J temperature during 100µs 10% pulse is 84 °C
CW Load Line of 2.1 mm device at 75 V

No gate – drain lag due to traps is observed!

As $V_{DD}$ increases, $P_{RF}$ and $P_{DISS}$ increase hence $T_J$ increases and $I_{DS_{SAT}}$ drops!

measured data on 2.1mm unit cell taken at University of Ferrara courtesy of Prof. G. Vannini, A. Raffo and G. Bosi, Dept. of Eng.
CW Load Line of 1.2 mm device at >100 V

No gate – drain lag due to traps is observed!

As $V_{DD}$ increases, $P_{RF}$ and $P_{DISS}$ increase hence $T_J$ increases and $IDS_{SAT}$ drops!

measured data on 1.2mm unit cell taken at University of Ferrara courtesy of Prof. G. Vannini, A. Raffo and G. Bosi, Dept. of Eng.
Future Work & Conclusions
Exploring $V_{DD} > 100$ V


With ~ 400 W at 150 V, why not 1 kW with a single-ended device?
At $V_{DD} = 150$ V

2x 15mm devices operated at 150 V

800 W with > 70% drain efficiency, 410 – 450 MHz

1 kW at $V_{DD} = 150$ V

3x 15mm devices operated at 150 V > 1 kW

1 kW with > 75% drain efficiency, 420 – 450 MHz

Could do 2 kW or more with 7x 15mm or larger devices in dual lead package

VISIT US at CSICS-2016 for more info


What about CW operation?
**ISM CW Applications – 430 & 915 MHz**

200 W CW, 80%,
430 MHz at 100 V

100 W CW, >60%,
915 MHz at 100 V

100 W CW at 100 V for GPS-2

One amplifier for 3 bands!

L1 – band
1575 ± 50 MHz

L2 – band
1225 MHz

L5 – band
1175 MHz

VISIT US at PAWR-2017 for more info

Conclusions

• Developed high $BV_{\text{DSS}}$ RF GaN transistors for UHF pulse radar amplifiers, but also exploring CW & other frequencies.

• Used harmonic tuning for switch-mode high efficiency PA

• Designed and built 1 kW module, TRL 4-6

• Need Phase 3 for space qualification

• What else can this technology enable? HE broadband PA? multi-band Pas? ...

Assessing Official Comments “The research effort conducted by the contractor clearly shows that the technology was viable. The contractor innovation demonstrated that the use of GaN Transistor Device for Optimum P-Band performance can be used for Multi-Mission Subsurface Imaging Radar (MMSIR). … This technology can benefit many areas in future radar systems. Future work is very highly recommended for SBIR contract as well as standalone research and development contract.”

ADDITIONAL/OTHER The contract enabled Integra to develop high voltage GaN technology for multiple applications that did not exist before.
Acknowledgements

Tushar Thrivikraman (Tech. Monitor)
Gregory Sadowy (Supervisor)

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