L-Band Floating-Ground RF Power Amplifier for Reverse-Type Envelope Tracking Systems

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Outline

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• Floating-Ground Transistor
• Amplifier Design
• Amplifier Testing
• Supply Modulation
• Conclusions & Outlook
Motivation: Efficiency Enhancement

Classical envelope tracking (ET) topology

• RF power amplifier (RF PA)
  – Fixed, common ground (GND)
  – High-voltage supply can be modulated

• Envelope amplifier (EA, e.g. buck converter)
  – Modulation of RF PA supply voltage
  – Fast switching for high instantaneous bandwidth (IBW)
  – Feasible with GaN-HEMT-based switch
    • Fast, but only n-type devices
    • Isolated switch driver
    • Bandwidth reduction due to parasitic capacitances!

Diagram illustrating the classical envelope tracking topology with an envelope amplifier (EA) modulating the RF power amplifier (RF PA).
Motivation: Efficiency & Bandwidth

Alternative ET topology*

- **EA**
  - Reverse-topology buck converter
  - Modulation of RF PA DC & LF GND
  - RF power GaN-HEMT for fast switching
  - GND-referenced switch control (no galvanic isolation!)
  - Bandwidth enhancement! 😊

- **RF PA**
  - Fixed high-voltage supply
  - Challenge: ground separation
    - Fixed RF GND
    - “Floating” DC & LF GND 😞

*Research project funded by ESA-ESTEC (NPI, “Improved Envelope Tracking Systems Based on VHF Switching Converter and RF Amplifier”)*
Pre-Work: Floating-Ground Transistor

• Core element of floating-GND RF PA*
• Package: modified 2-lead Kyocera RF power package (input lead, RF output lead and DC & LF GND lead)
• Transistor without via hole connection to backside
• RF bypass to system GND
  – single-layer capacitor $C_{\text{GND}}$ with SRF slightly above pass-band frequency

Amplifier Design (I)

Overview

• L-Band (around 1.5 GHz)
• Hybrid design based on load-pull measurements and simulations
  – PCB
    • 20 mil Rogers 4003C
  – Transistor
    • FBH RF power GaN-HEMT (16 mm gate width, 0.5 um gate length)
  – C_GND
    • 330 pF SLC
Amplifier Design (II)

Input network

• Stabilization
  – Account for influence of floating GND!
  – Different measures for in- and out-of-band stability ($\Gamma_S$ reduction)
    • In-band: $C_{RF} + R_{Stab,IN}$
    • Out-of-band: $R_{Stab,OUT}$
    • Challenge: LF-RF transition region

• Matching
  – To $Z_{IN}^* \approx 4 \, \Omega$ of floating-GND transistor
  – TL_{IN2}: dimensions determined by lead dimensions
  – Impedance shift due to stability network
  – TL_{IN1}: transformation to 50 $\Omega$
Amplifier Design (III)

Output network

- Matching based on load-pull
  - Simulations and measurements
  - Trade-off: power versus efficiency
  - Target impedance $Z_L \approx (5+j\cdot2) \, \Omega$

- Practical realization
  - $T_{L_{OUT1}}$: dimensions determined by lead dimensions
  - $C_{\text{Match}}$: compensation of reactive part
  - $T_{L_{OUT2}}$: $\lambda/4$ transformation to 50 $\Omega$
Drain & source biasing networks

- $I_{\text{DC+LF}}$ through drain and DC&LF source terminals
  - Wideband bias paths required
- RF isolation
  - $\lambda/4$ stubs, short-circuited by capacitors $C_{\text{Stub}}$
- Main bandwidth limitation: transistor-internal $C_{\text{GND}}$
Amplifier Design (V)

Gate biasing network

- Variation of the gate potential according to the modulation of the source potential
- Low-pass filter \((C_{\text{Filter,GS}})\) placed between gate and source paths
- RF isolation: \(L_{\text{Feed}}\)
- Improvement of LF stability: \(R_{\text{Feed}}\)
- External galvanically isolated gate supply to apply constant \(V_{\text{GS}}\)
Amplifier Testing (I)

LF Paths

- Cold 3-port S-parameter measurements at external $V_{\text{Gate}}$, $V_{\text{Drain}}$, $V_{\text{Source}}$ terminals
- Re-simulation in ADS (AC)
- Frequency responses (assumption: 20 $\Omega$ load, complies to average load formed by RF PA)
- Tight wideband coupling up to about 80 MHz
S-parameters (RF path)

- Operating conditions
  - Biasing: low class AB
  - $V_{DS} = [10 \ldots 40\,\text{V}]$, $V_S = [0\,\text{V}, 20\,\text{V}]$
  - Frequency range: $[10\,\text{MHz} \ldots 2.5\,\text{GHz}]$

- Fairly poor input matching and only conditional stability
  - $|S_{11}| \approx [-7\,\text{dB} \ldots -6\,\text{dB}] @ 1.4\,\text{GHz}$
  - $|S_{11}| > 0\,\text{dB} @$ approx. $500\,\text{MHz}$ for $30\,\text{V}$ & $40\,\text{V}$

- High gain, increase with $V_{DS}$
  - $|S_{21}| \approx 10\,\text{dB} @ 1.1\,\text{GHz}$
  - $|S_{21}| > 16\,\text{dB} @ 1.3\,\text{GHz}$

- Fairly good output matching @ $[1.2\,\text{GHz} \ldots 2.2\,\text{GHz}]$
  - $|S_{22}| < -10\,\text{dB} @ V_{DS} = [30\,\text{V}, 40\,\text{V}]$
  - $|S_{22}| \approx [-8\,\text{dB} \ldots -5\,\text{dB}] @ V_{DS} = 10\,\text{V}$

- Results for $20\,\text{V}$ offset: almost identical
Amplifier Testing (III)

Large signal operation (freq.)

- Operating conditions
  - $V_{DS} = 40$ V, $V_S = 0$ V
  - Frequency range: [1 GHz … 2 GHz]
  - Different available source power ($P_{avs}$) levels
- $P_{avs} = 10$ dBm (low power)
  - good agreement to the $S$ parameter tests
- Saturated $P_{out}$ (gate starts to draw current)
  - $P_{out} = [46.6$ dBm … $47.4$ dBm]
    (maximum @ 1.3 GHz)
  - Gain $\approx 10.5$ dB @ 1.3 GHz & 7.5 dB @ 1.6 GHz
Amplifier Testing (IV)

Large signal operation (power)

- **Operating conditions**
  - $V_{DS} = [30 \text{ V, } 40 \text{ V}], V_S = 0 \text{ V}$
  - Frequencies: 1.3 GHz, 1.45 GHz, 1.6 GHz
  - $P_{avS}$ range: [10 dBm ... max]

- **Gain**
  - Reduction over the band
  - 1 dB gain difference for the voltages

- **Power-added efficiency (PAE)**
  - Reduction for increasing frequencies
  - Max(PAE) > 57% @ 1.3 GHz & 30 V
  - Mismatch @ 1.3 GHz & 1.45 GHz: PAE(30 V) > PAE(40 V)
Supply Modulation

Back-off efficiency enhancement

• Max. efficiency improvement @ 1.3 GHz
  – 12%-pt. @ 3 dB OPB (V_{DS} reduced to 30 V)
• Clear improvement at all frequencies
  – Frequency-dependent
  – Influence of RF PA matching
• Good ET candidate
Conclusions & Outlook

Conclusions

• First-ever shown floating-GND RF PA with packaged floating-GND RF power GaN-HEMT
• Good performance without any tendency to oscillate during measurements
  – Verified source voltage offset performance
  – Excellent power performance: 55 W max(P_{out}), 57% max(PAE) @ 1.3 GHz
  – Large possible LF bandwidth: 80 MHz
• Excellent back-off efficiency improvement (12%-pt. @ 3 dB OPB)
• Novel 4-terminal floating ground transistor but textbook design process

Outlook

• Concept verification in highly efficient and wideband reverse-type ET systems for L, C, and S-band
Acknowledgment

This work was partly supported by

• ESA-ESTEC within the NPI “Improved Envelope Tracking Systems Based on VHF Switching Converter and RF Amplifier”

• The German BMBF within the Research Fab Microelectronics Germany (FMD) under ref. 16FMD02

Thank you!
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