Integration of GaN Supply Modulators and RF Power Amplifiers

Dragan Maksimovic
maksimov@colorado.edu
Colorado Power Electronics Center (CoPEC), ECEE Department
University of Colorado - Boulder

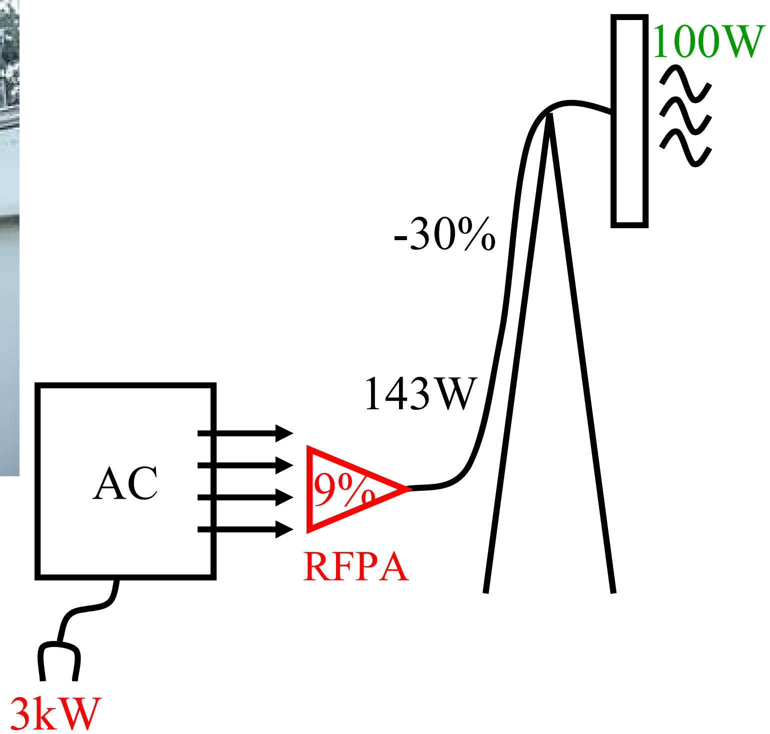
Yuanzhe Zhang[1], Dr. Miguel Rodriguez[1]*, Andrew Zai[2], Dr. David Sardin[2], Prof. Zoya Popovic[2]

[1]CU-Boulder Colorado Power Electronics Center (CoPEC): drain supply modulators
[2]CU-Boulder microwaves research group: RFPAs and transmitter systems
[1]*now with AMD

PWR'14 SOC
Integrated Power Conversion and Power Management
next generation technology for emerging business opportunities
new technologies new applications new markets

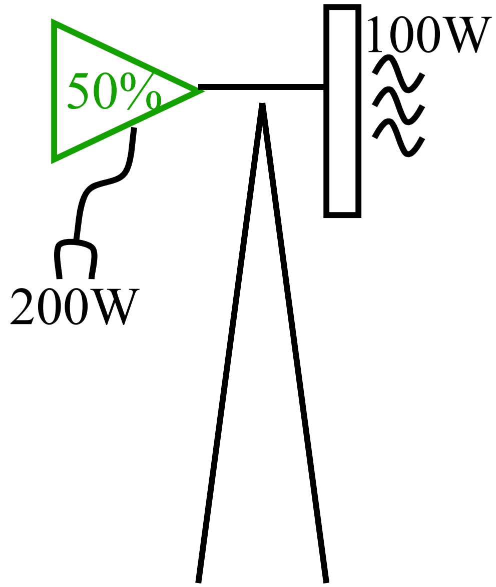
System: RF Transmitters

4G base station example



Each site has between 3 and 12 transmitters!

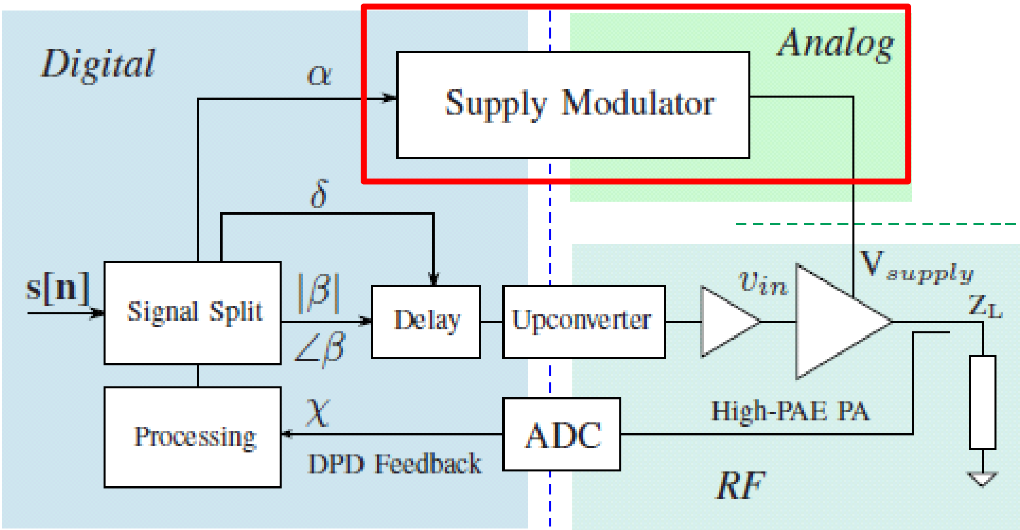
System Efficiency Improvement Objectives



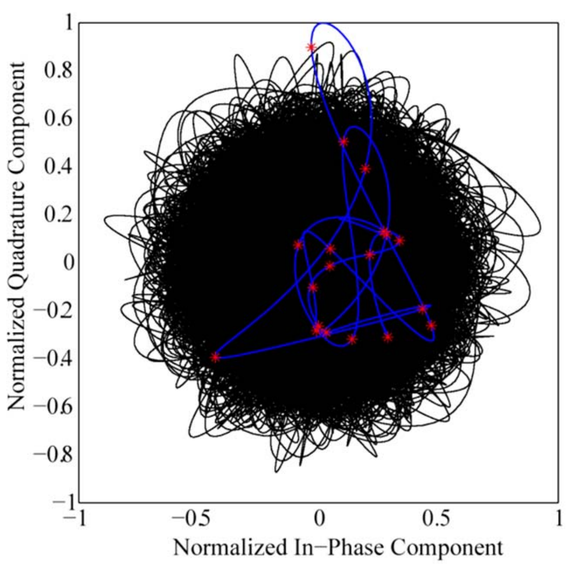
- **Higher reliability**
- **Lower system cost**
- **+In mobile platforms: battery life**

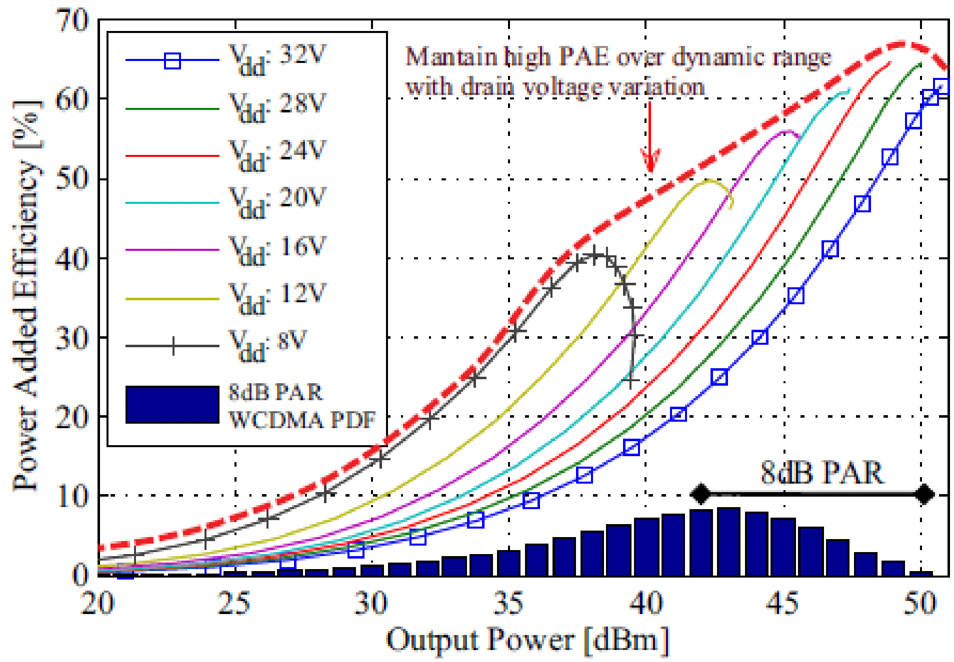
Requires systems approach, co-design of architecture, baseband, RF, and power electronics

Supply Modulation Approach

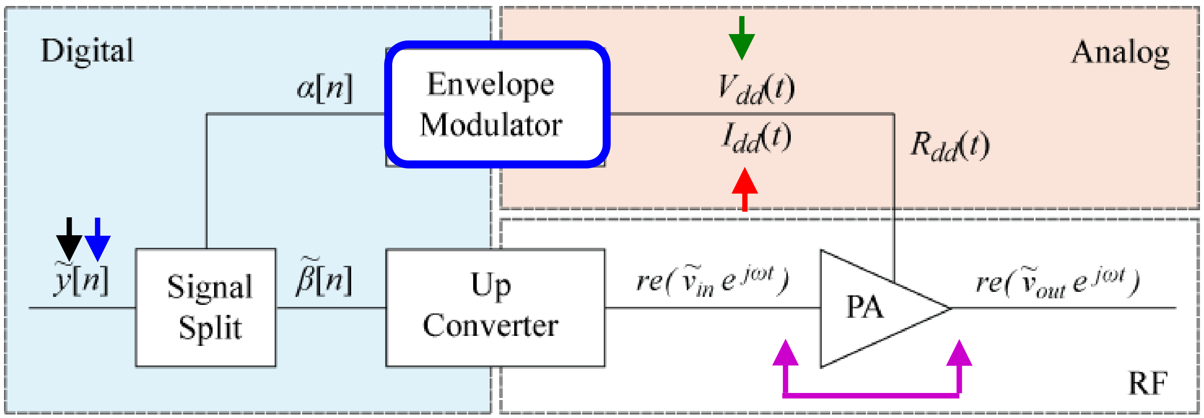


Supply modulator performs a form of "envelope tracking" (ET) to achieve linearity and efficiency improvements

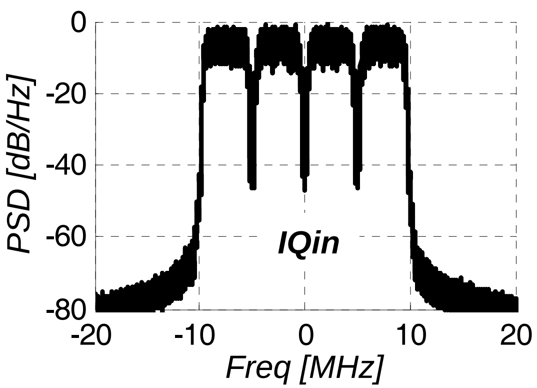


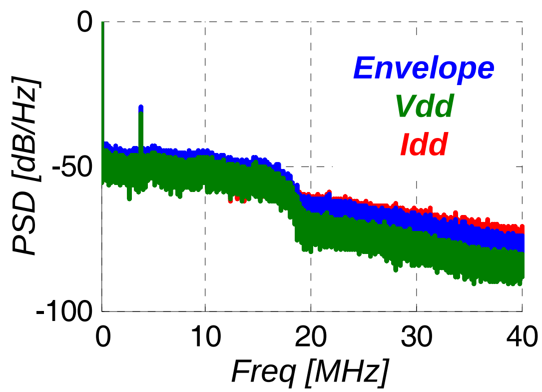


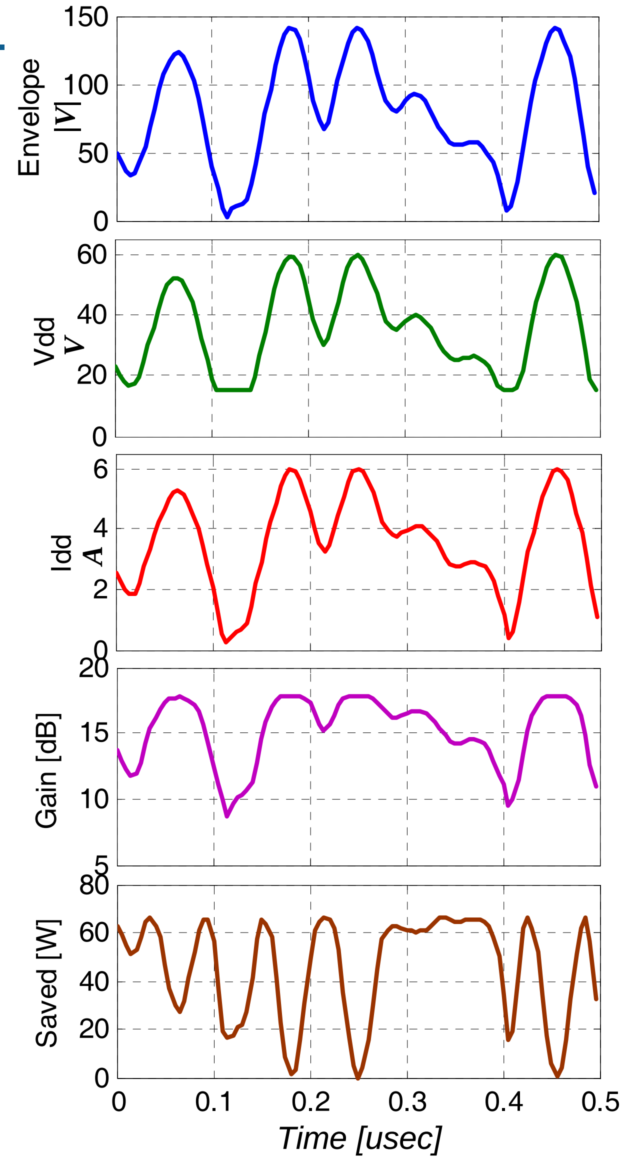
System Operation[1]



20MHz 40W BTS ET Transmitter





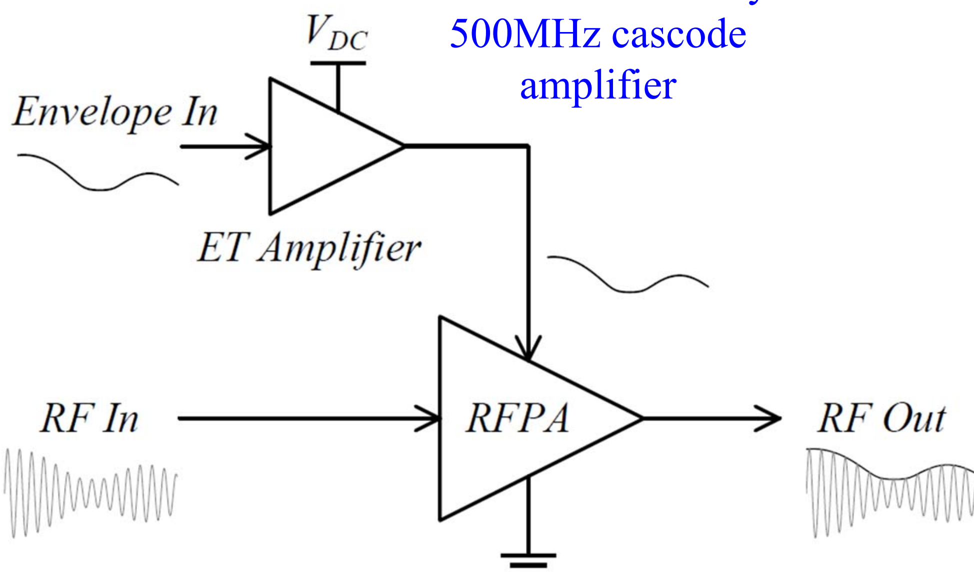


Note: envelope BW can be substantially larger than baseband signal BW

[1] J. Hoversten, S. Schafer, M. Roberg, M. Norris, D. Maksimovic, and Z. Popovic, "Codesign of PA, Supply, and Signal Processing for Linear Supply-Modulated RF transmitters," IEEE Trans. Microw. Theory Tech. 2012

PwrSOC: ET Transmitter on a Chip

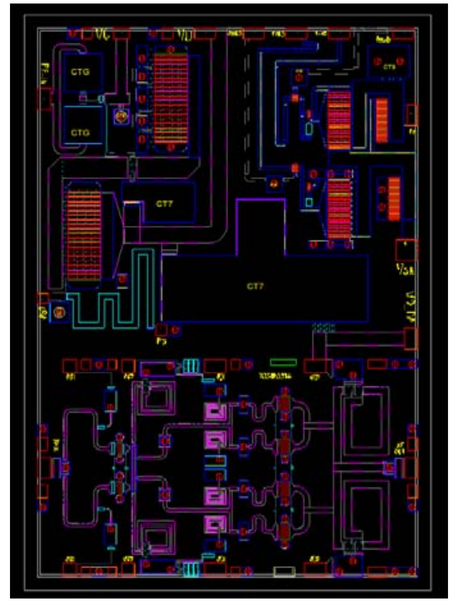
High-frequency (100MHz), wide-bandwidth (20MHz) switcher assisted by 500MHz cascode amplifier



Saturated, harmonically terminated, high-efficiency RFPA

5.4 x 3.8 mm in GaN-on-SiC RF process

Cascode ET amp, 500 MHz BW [5, 6]

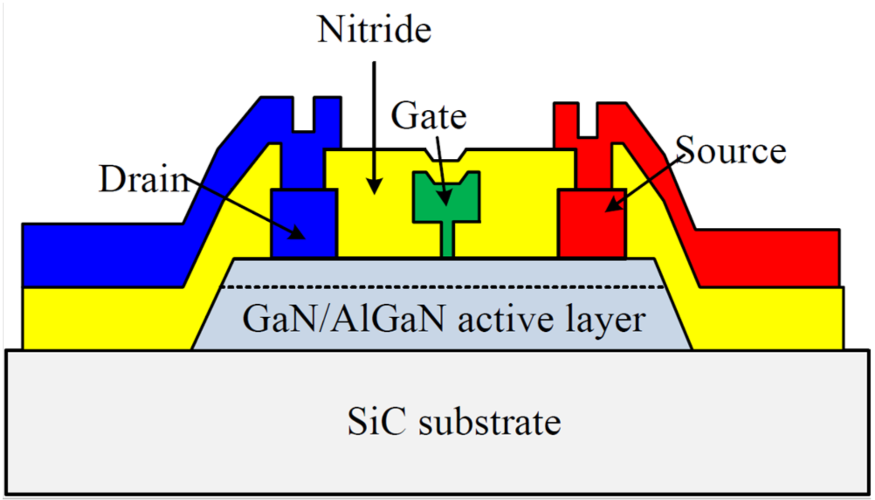


100MHz switching ET amp, 20MHz BW [8, 9]

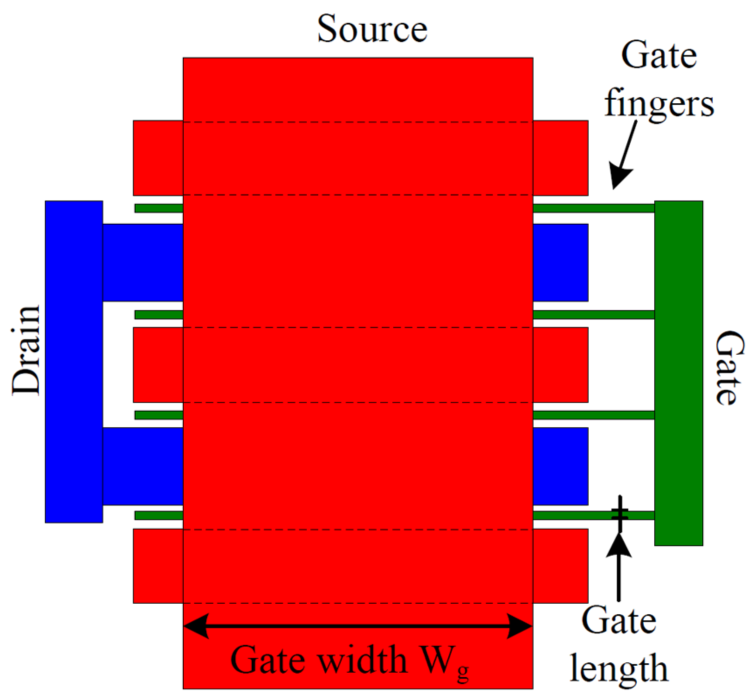
10W, X-Band RFPA [2, 3, 4]

D-mode GaN-on-SiC 0.15 μm RF process

- Intended for RF applications, e.g. RFPA’s, MMIC’s
- Depletion-mode, n-type only, threshold voltage $V_T \approx -3.5$ V
- Device size (gate periphery) $W = N \cdot W_g$
  - N = number of gate fingers
  - W_g = gate width

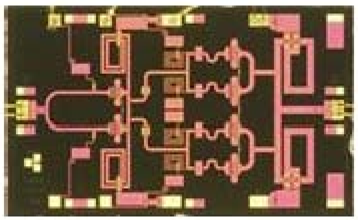


GaN-on-SiC HEMT basic unit cell



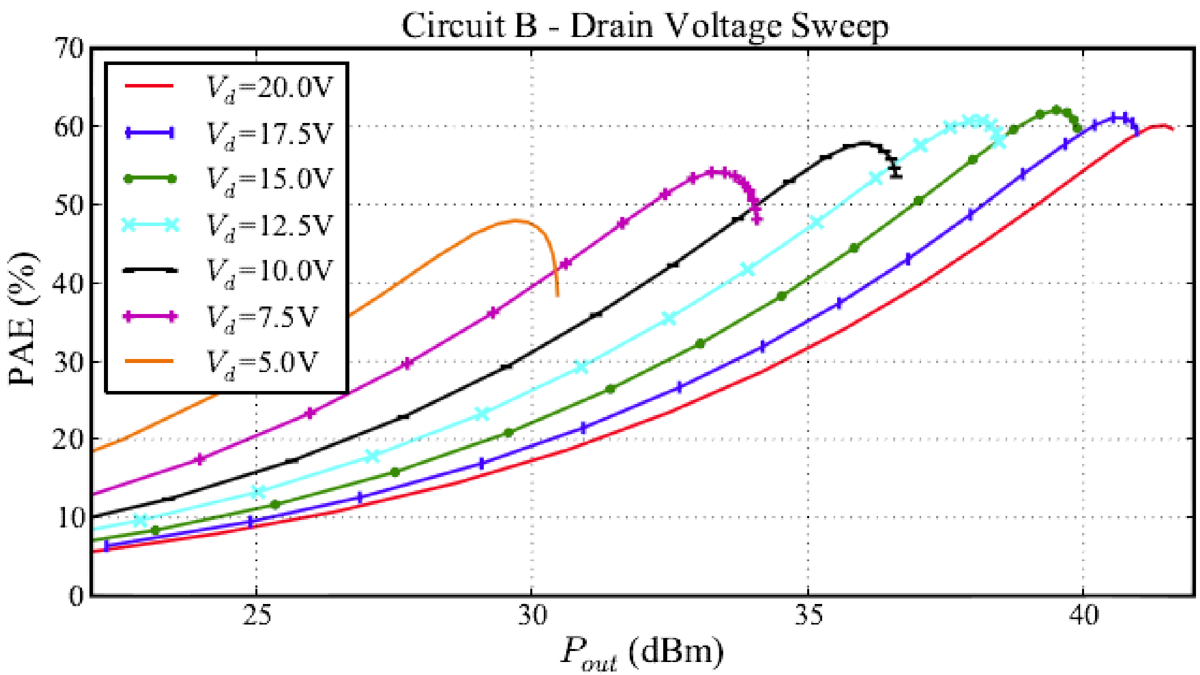
Simplified device layout with 4 parallel cells

RF PA MMIC Design Example[3]



3.8 x 3.2 mm

- Two-stage X-band (10 GHz) power amplifier MMIC
- Class-E output stage: four 0.9 mm devices
- Gain: 20 dB, bandwidth: 1.6 GHz



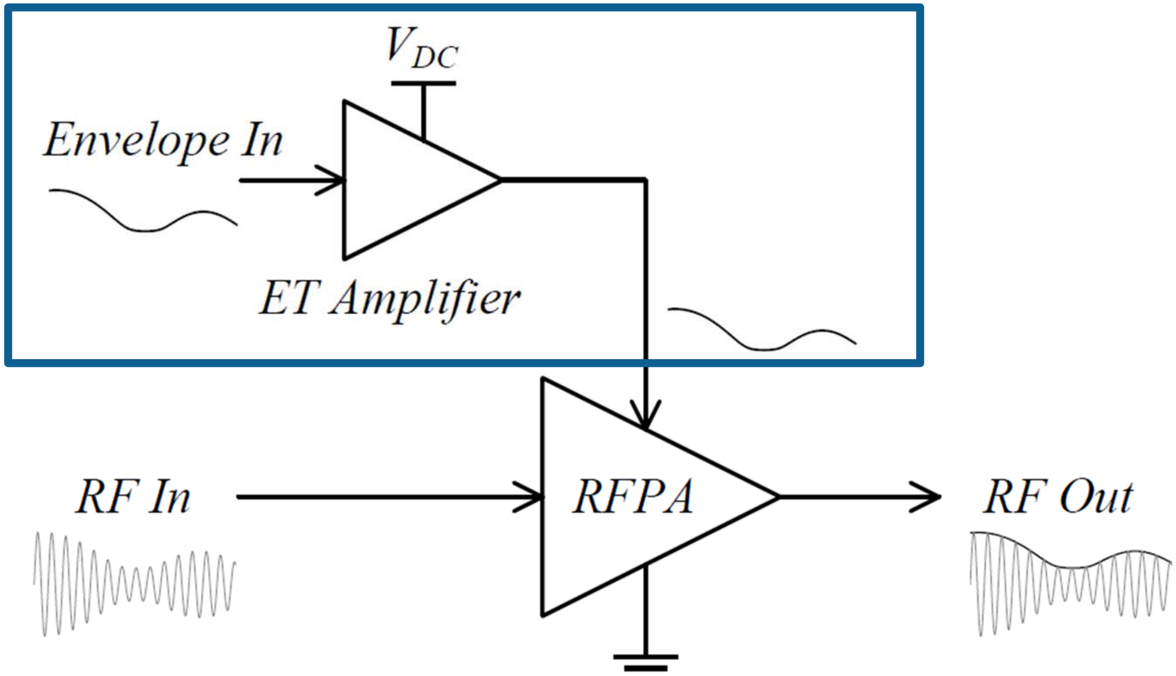
Power-added efficiency as a function of output RF output power at different drain supply voltages

Max PAE (%)	59.9
Max P_{out} (W)	13.2
Gate size (mm)	3.6
W/mm	3.68

[3] S. Schafer, M. Litchfield, A. Zai, C. Campbell, Z. Popovic, "X-Band MMIC GaN Power Amplifiers Designed for High-Efficiency Supply-Modulated Transmitters," *IEEE MTT IMS 2013*, Seattle, WA, June 2013.

Very high frequency switching supply modulator

- Dynamic capabilities suitable for envelope tracking application
  - High bandwidth (20 MHz LTE envelope) and high efficiency (>80%) must be met simultaneously
- Possibilities for SOC integration in the same GaN-on-SiC RF process



Device switch characteristics

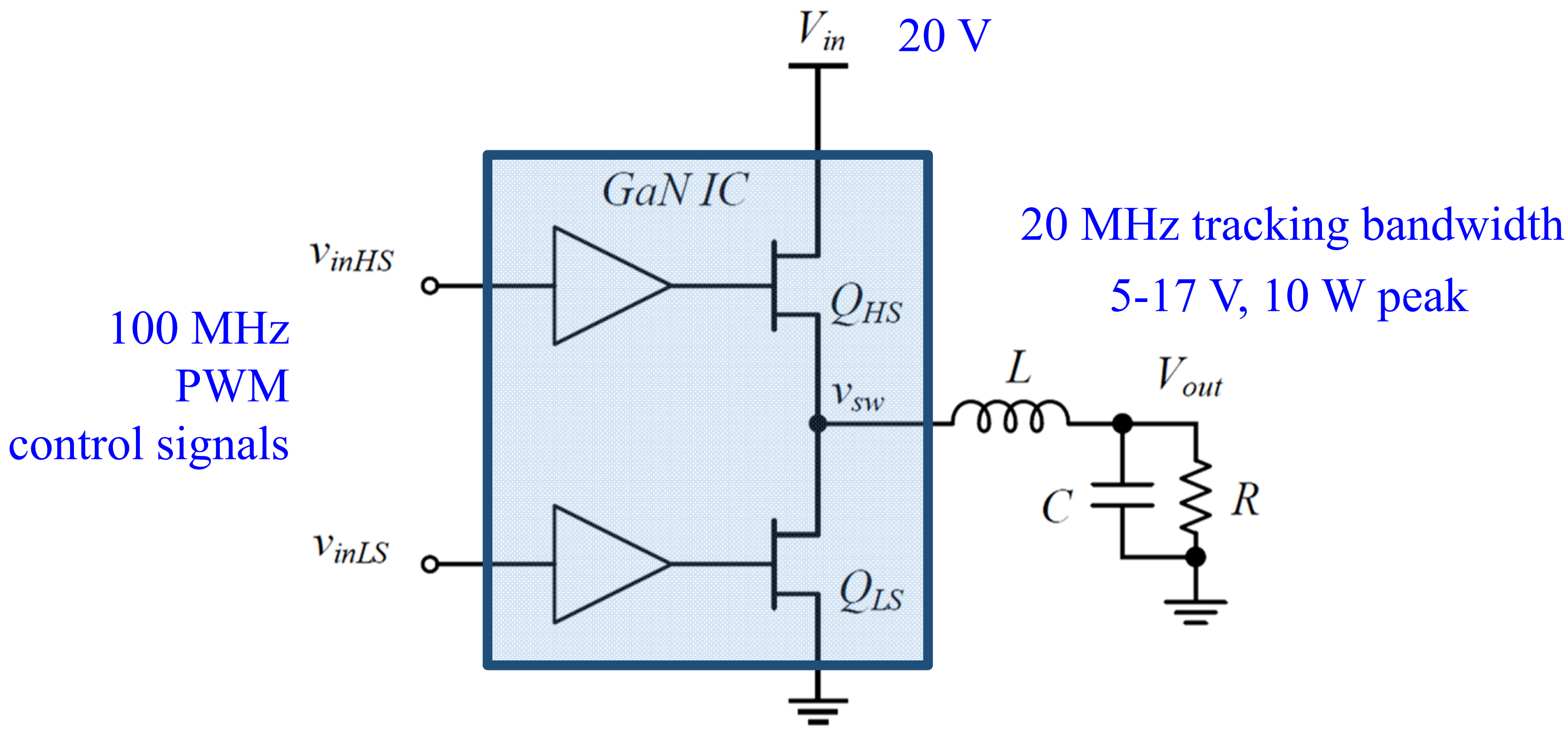
	$R_{on,s}$	$C_{oss,s}$	$C_{iss,s}$	$Q_{g,s}$
Simulated	2.1 Ω·mm	0.4 pF/mm	1.5 pF/mm	8.8 pC/mm

Comparison of 40V devices	**FOM = $R_{on,s}Q_{g,s}$ [pVs]**
Silicon MOSFET (e.g. Si 2318)	148
GaN-on-Si (e.g. EPC 8008)	58
RF GaN-on-SiC process	**19**

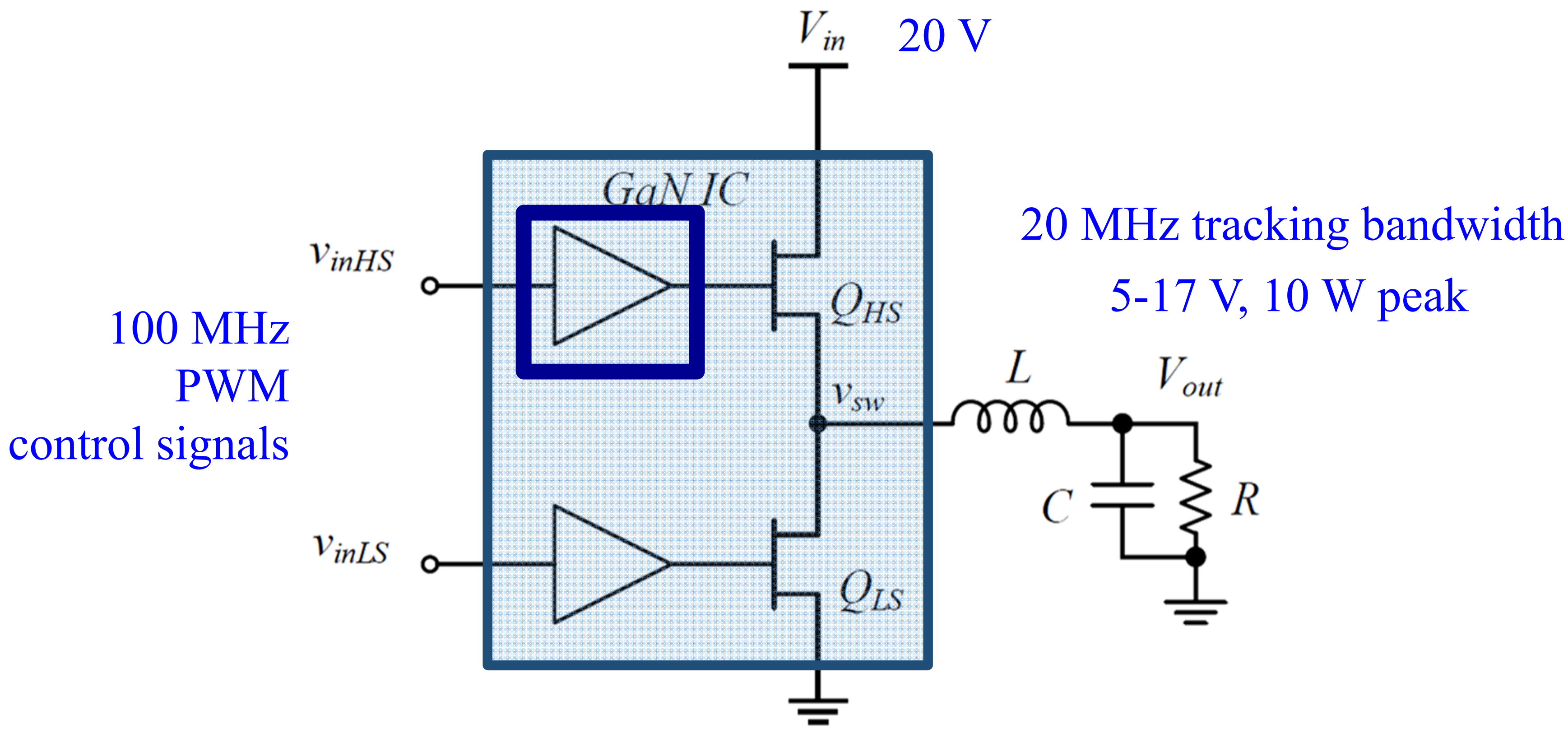
- Low device FOM
- Zero-voltage-switching (ZVS)
- Gate-drive integration

High-efficiency at very high switching frequency

100 MHz Integrated GaN PWM Buck Converter

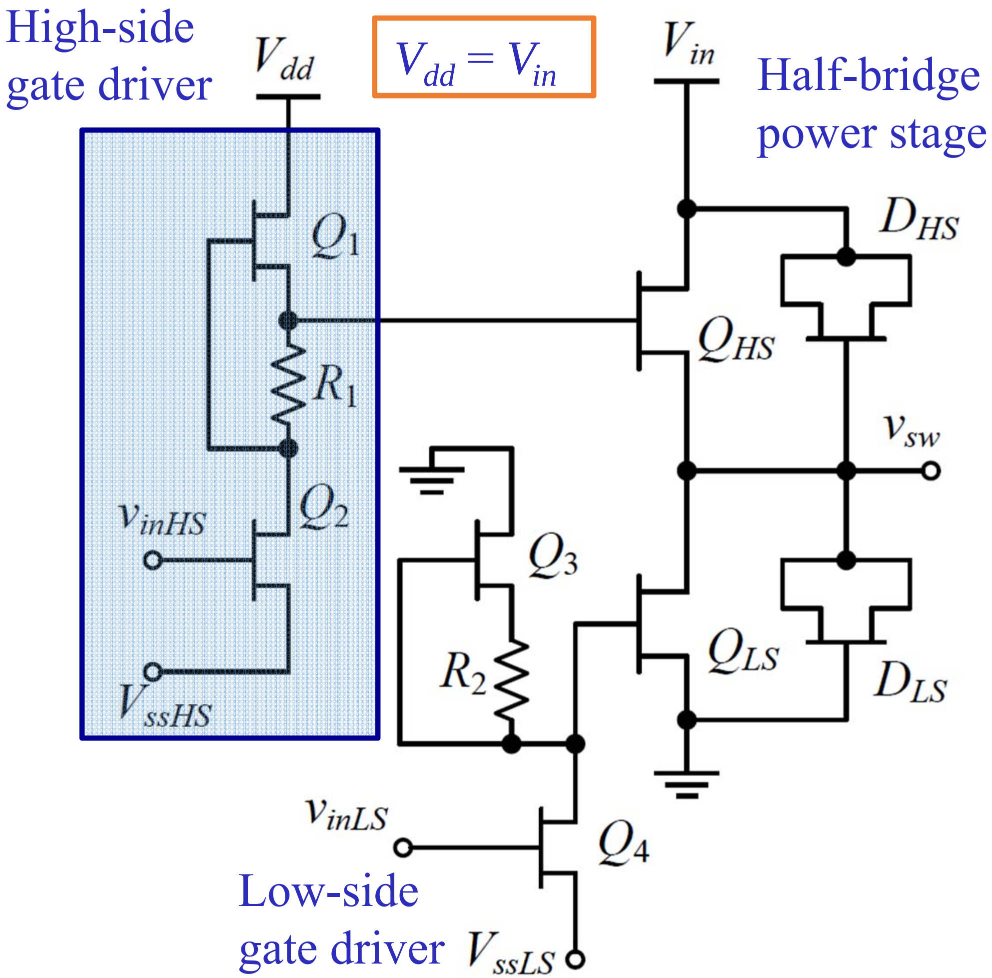


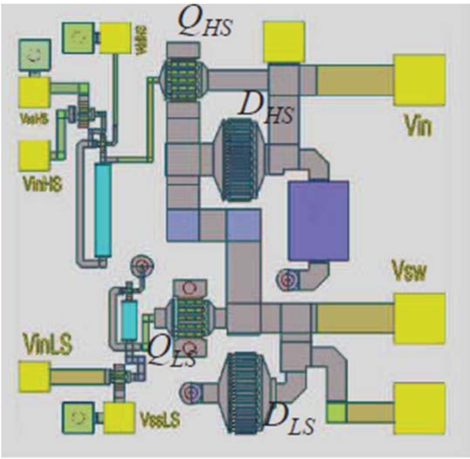
100 MHz Integrated GaN PWM Buck Converter



<u>Key challenge</u>: level-shifting high-side gate driver to support very high frequency (100 MHz) *PWM control*

Standard active pull-up driver





Chip layout: 2.4 × 2.3 mm

Half-bridge power stage
Q_{HS}/D_{HS}, Q_{LS}/D_{LS}

High-side gate driver
Q_1, R_1, Q_2

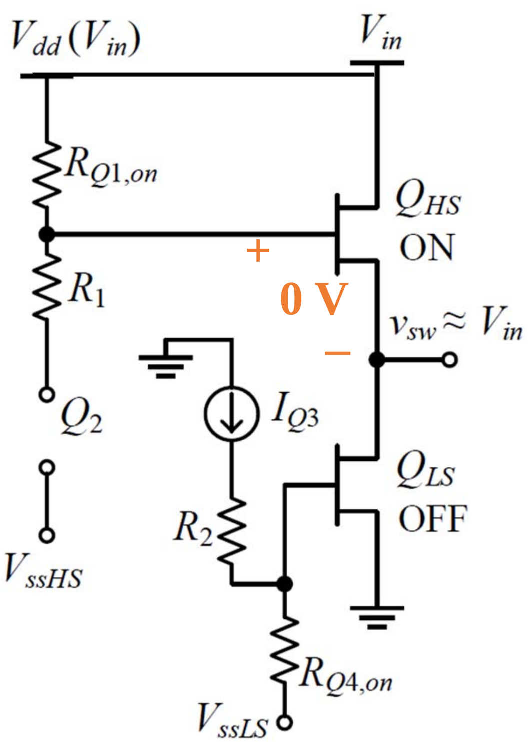
Low-side gate driver
Q_3, R_2, Q_4

Q_{HS}, Q_{LS}	D_{HS}, D_{LS}	Q_1, Q_3	Q_2, Q_4	R_1	R_2
10x125μm	10x120μm	2x25μm	4x50μm	300 Ω	125 Ω

Active pull-up driver operation

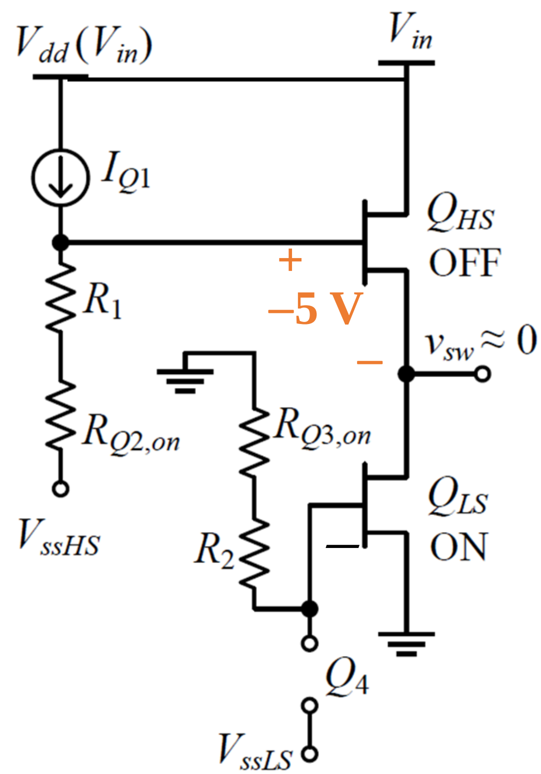
Q_{HS} on, Q_{LS} off

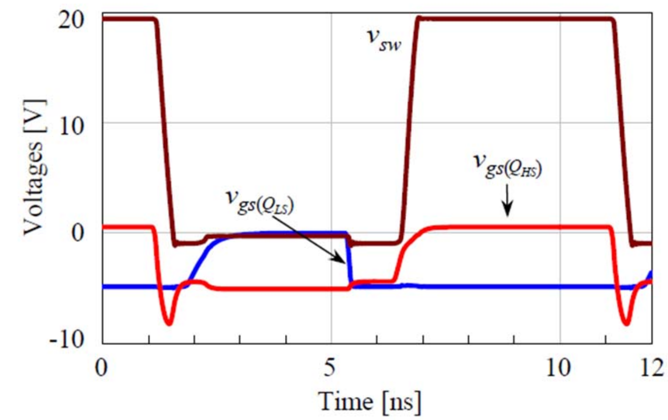
I_{Q3}=13.2 mA

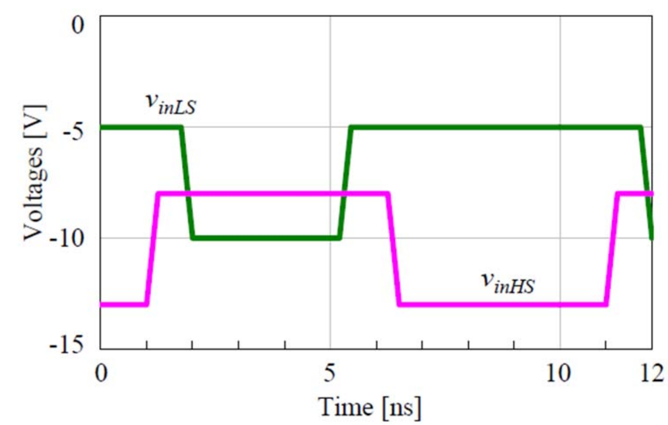


Q_{HS} off, Q_{LS} on

I_{Q1}= 8.5 mA





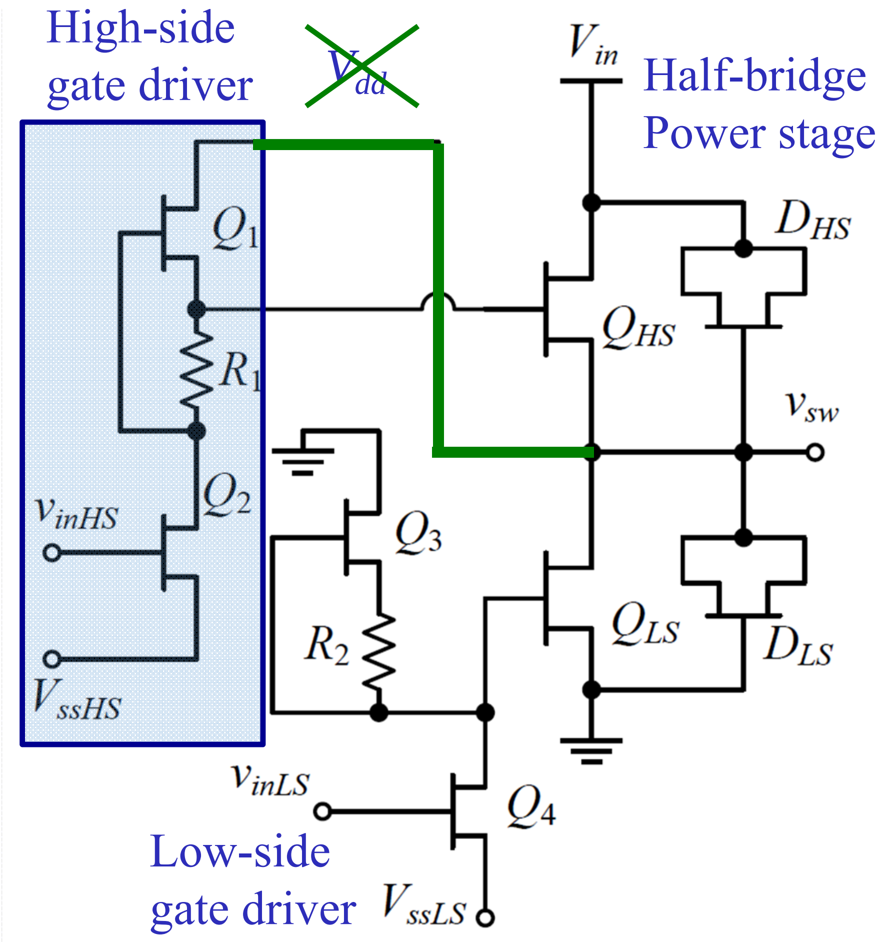


D=0.5, I_o=0.25 A

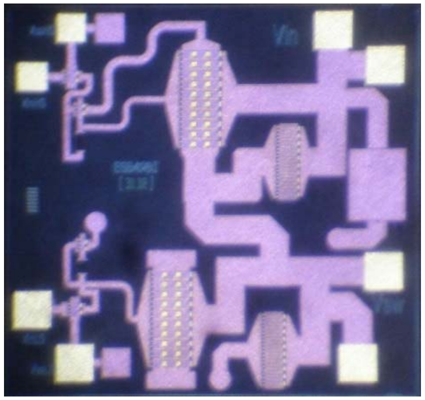
$$P_{d,conduction} = -DV_{ssLS}I_{Q3} + (1-D)(V_{in} - V_{ssHS})I_{Q1}$$

HIGH

Modified active pull-up driver[8,9]



Q_{HS}, Q_{LS}	D_{HS}, D_{LS}	Q_1, Q_3	Q_2, Q_4	R_1	R_2
20x200μm	20x100μm	4x25μm	4x50μm	100 Ω	75 Ω



Chip micro-photograph: 2.4 × 2.3 mm

Half-bridge power stage
Q_{HS}/D_{HS}, Q_{LS}/D_{LS}

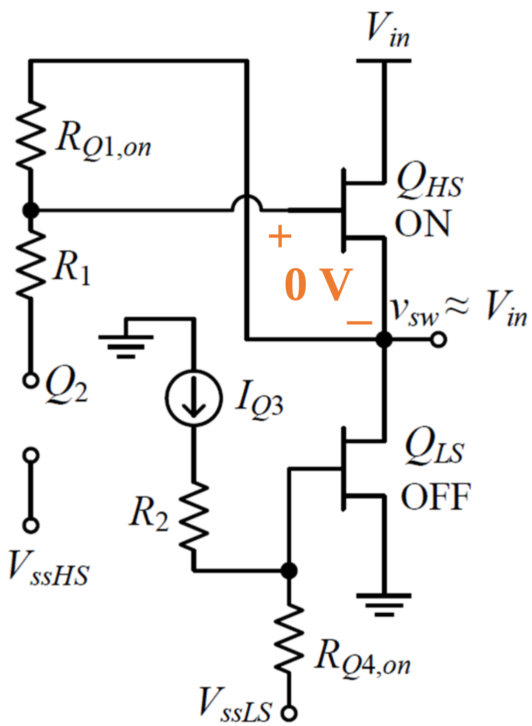
Half-side gate driver
Q_1, R_1, Q_2

Low-side gate driver
Q_3, R_2, Q_4

Modified active pull-up driver operation

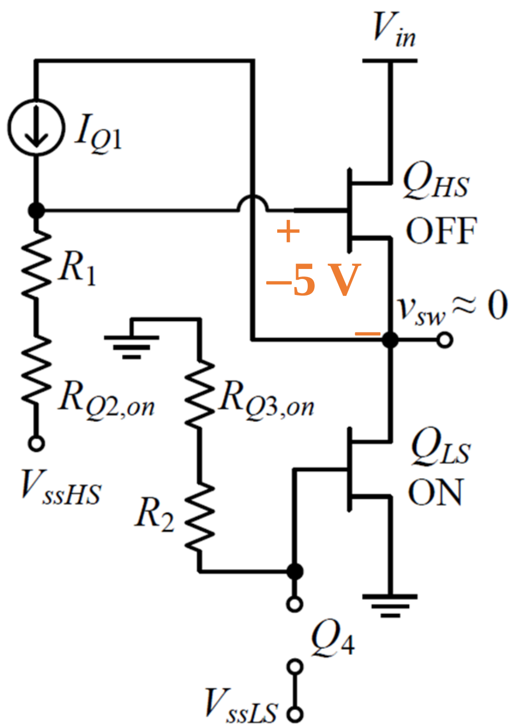
Q_{HS} *on*, Q_{LS} *off*

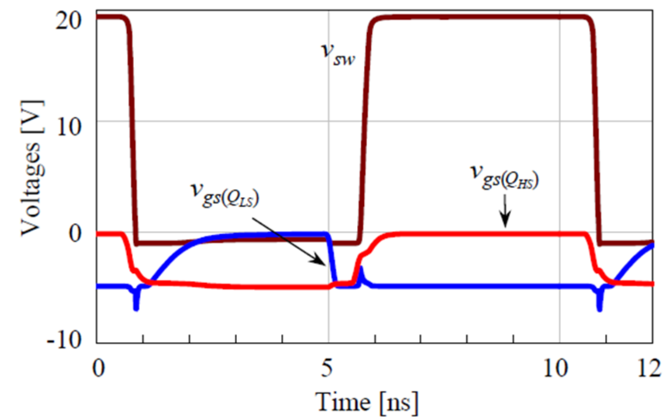
I_{Q3}=25.6 mA

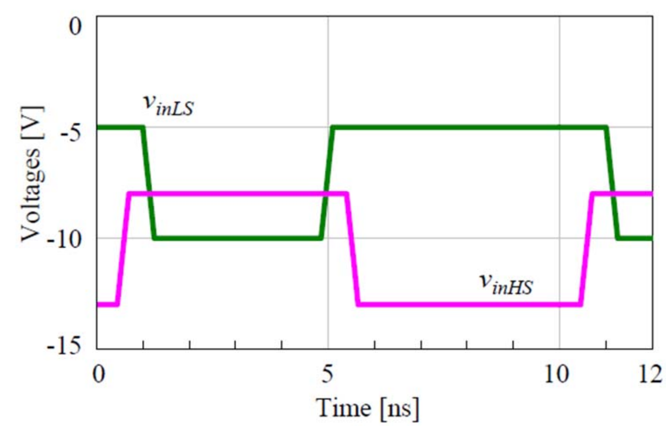


Q_{HS} *off*, Q_{LS} *on*

I_{Q1}= 23.3 mA







D=0.5, I_o=0.25 A

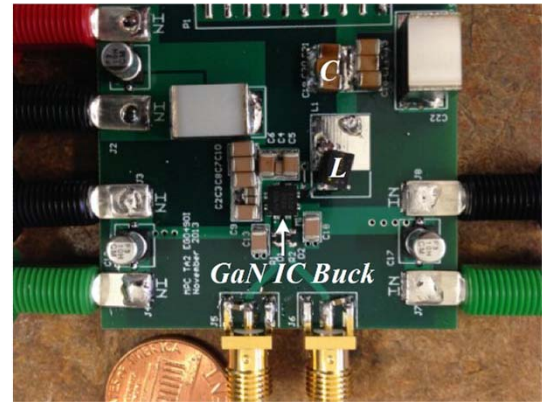
$$P_{d,conduction} = -DV_{ssLS} I_{Q3} + (1-D)(-V_{ssHS}) I_{Q1}$$

LOW

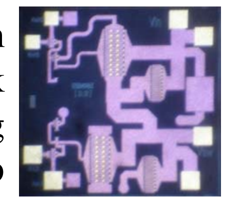
Low driver power loss, and no bootstrap capacitor required

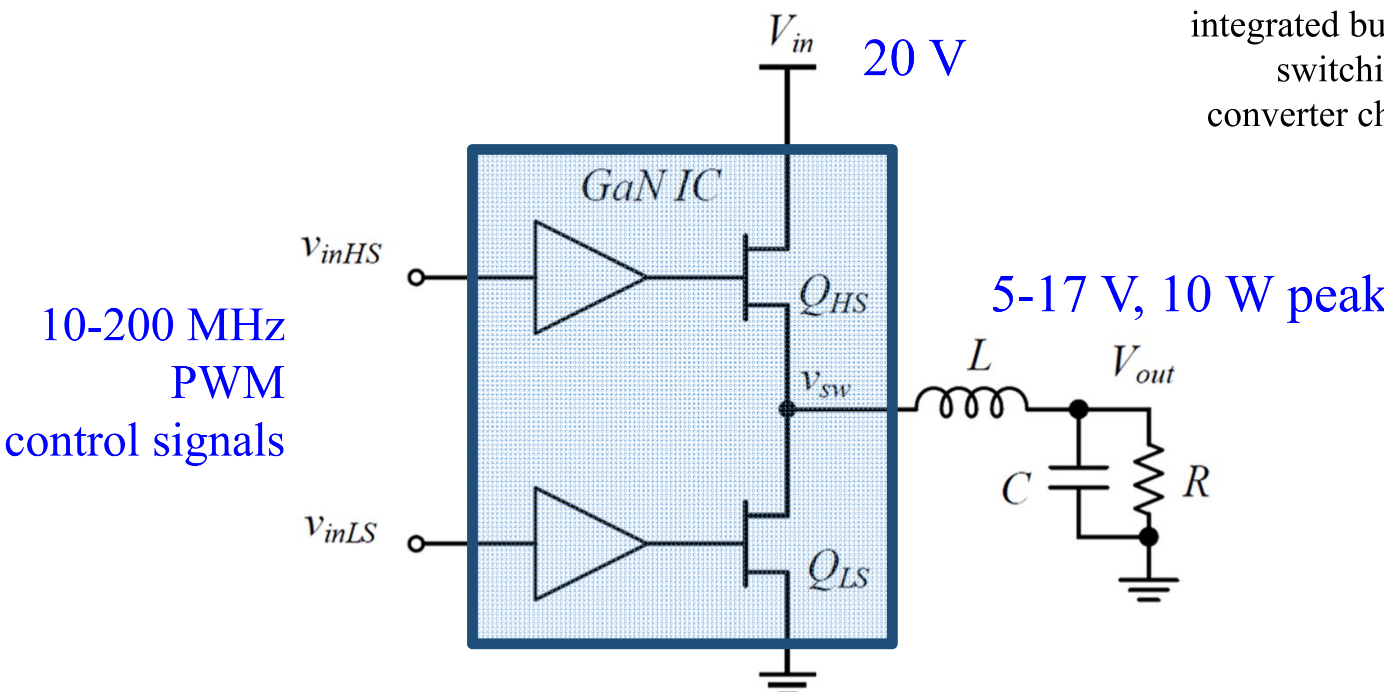
Experimental prototype

- 10-200 MHz PWM switching, ZVS operation (QSW)
- Control: Altera Stratix IV FPGA, 125 ps resolution
- Chip package: 20-pin 4x4mm QFN package
- Filter components
  - Low-ESR capacitors
  - High-*Q* air-core inductor (47 nH)

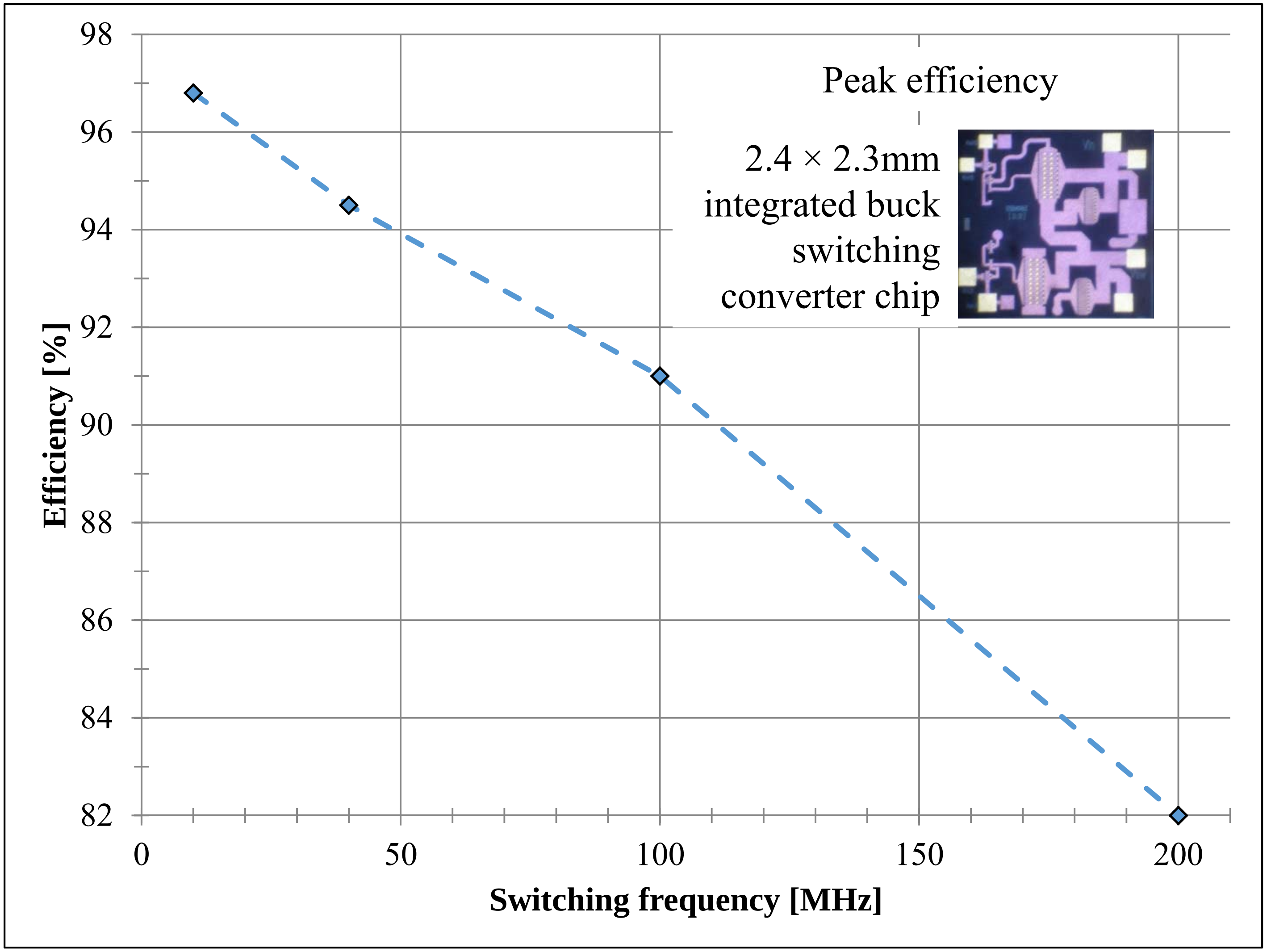


2.4 × 2.3mm integrated buck switching converter chip



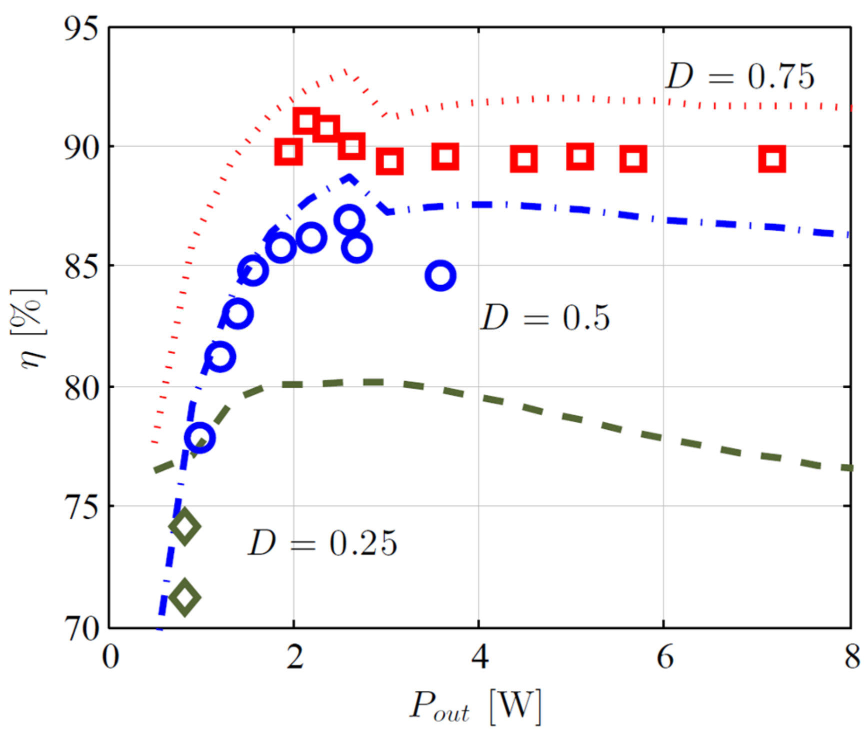


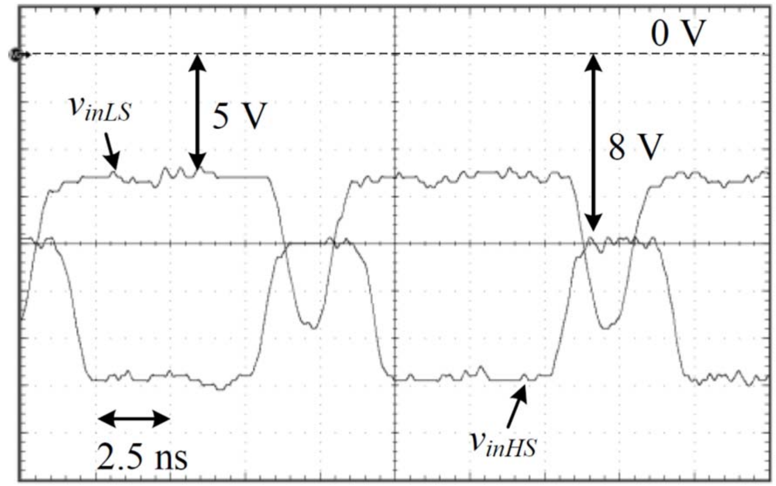
Efficiency as a function of switching frequency

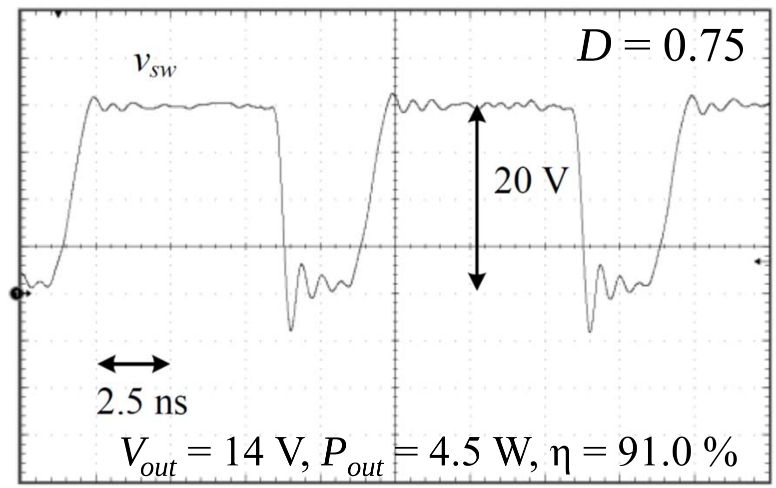


Experimental results at 100 MHz switching frequency

- P_{out} up to 7 W static
- ~ 0.2 W driver loss
- 91% peak power-stage efficiency

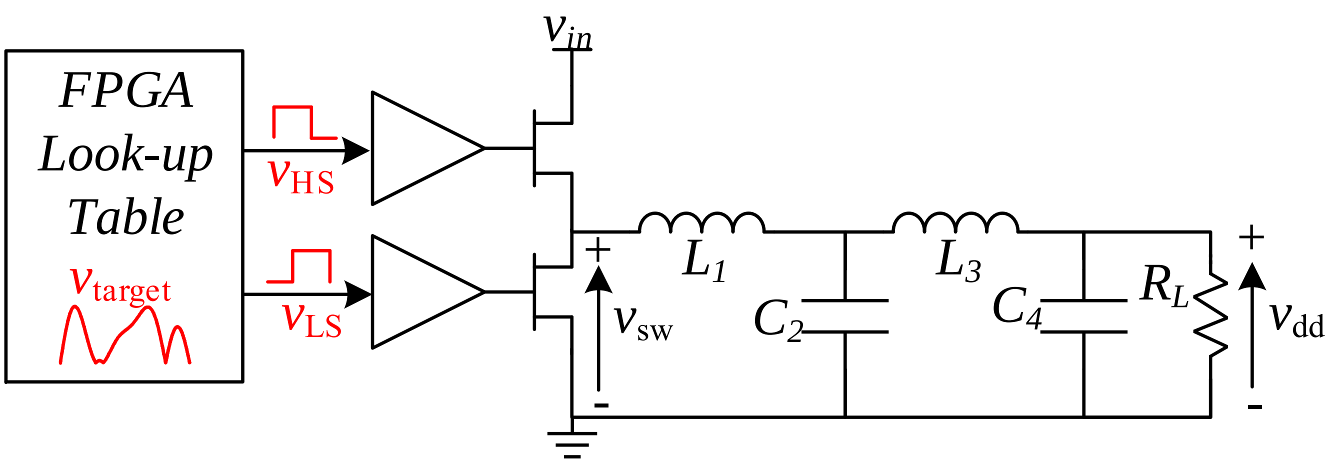






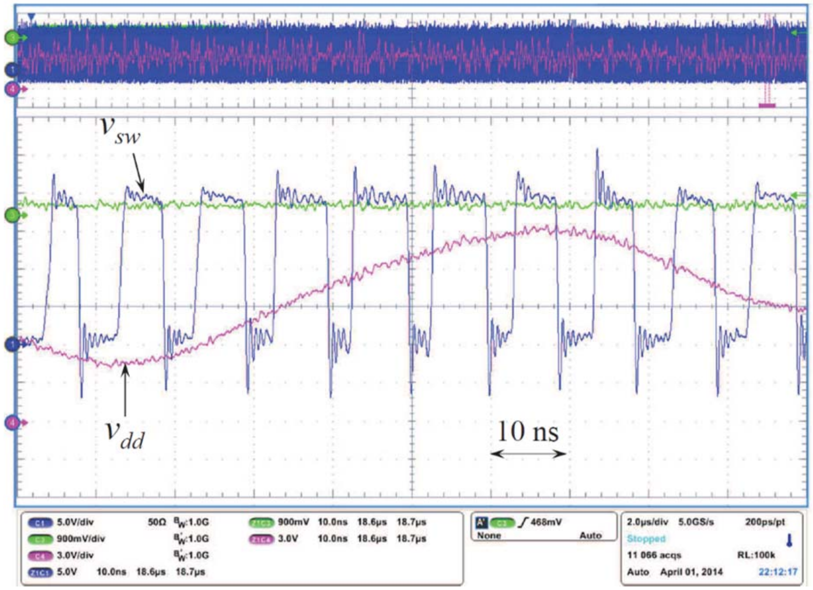
Application: envelope tracking supply for RFPAs

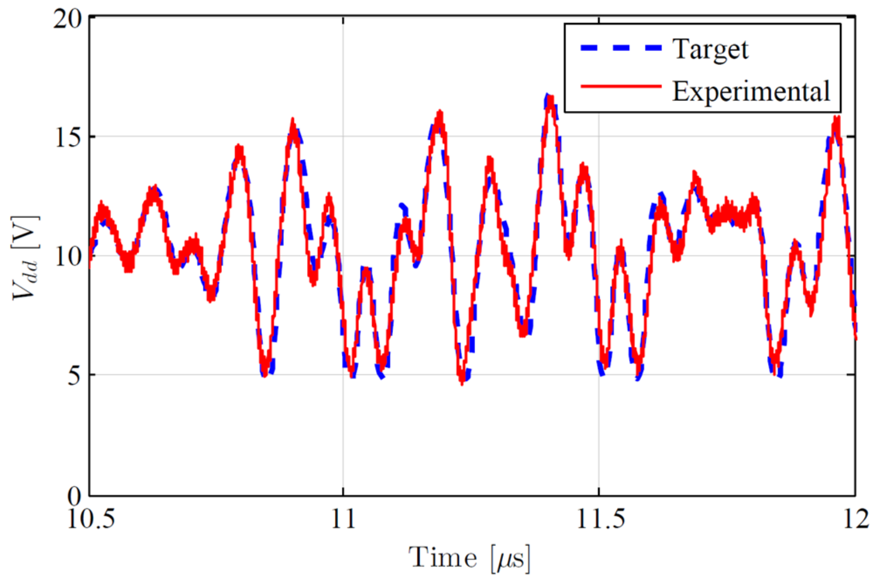
- Target signal: 20 MHz bandwidth LTE envelope
- 4th order filter, 25 MHz cut-off frequency
- 100 MHz switching frequency



L_1	C_2	L_3	C_4	R_L	V_{in}	$P_{out,pk}$
28 nH	820 pF	307 nH	270 pF	30 Ω	20 V	10 W

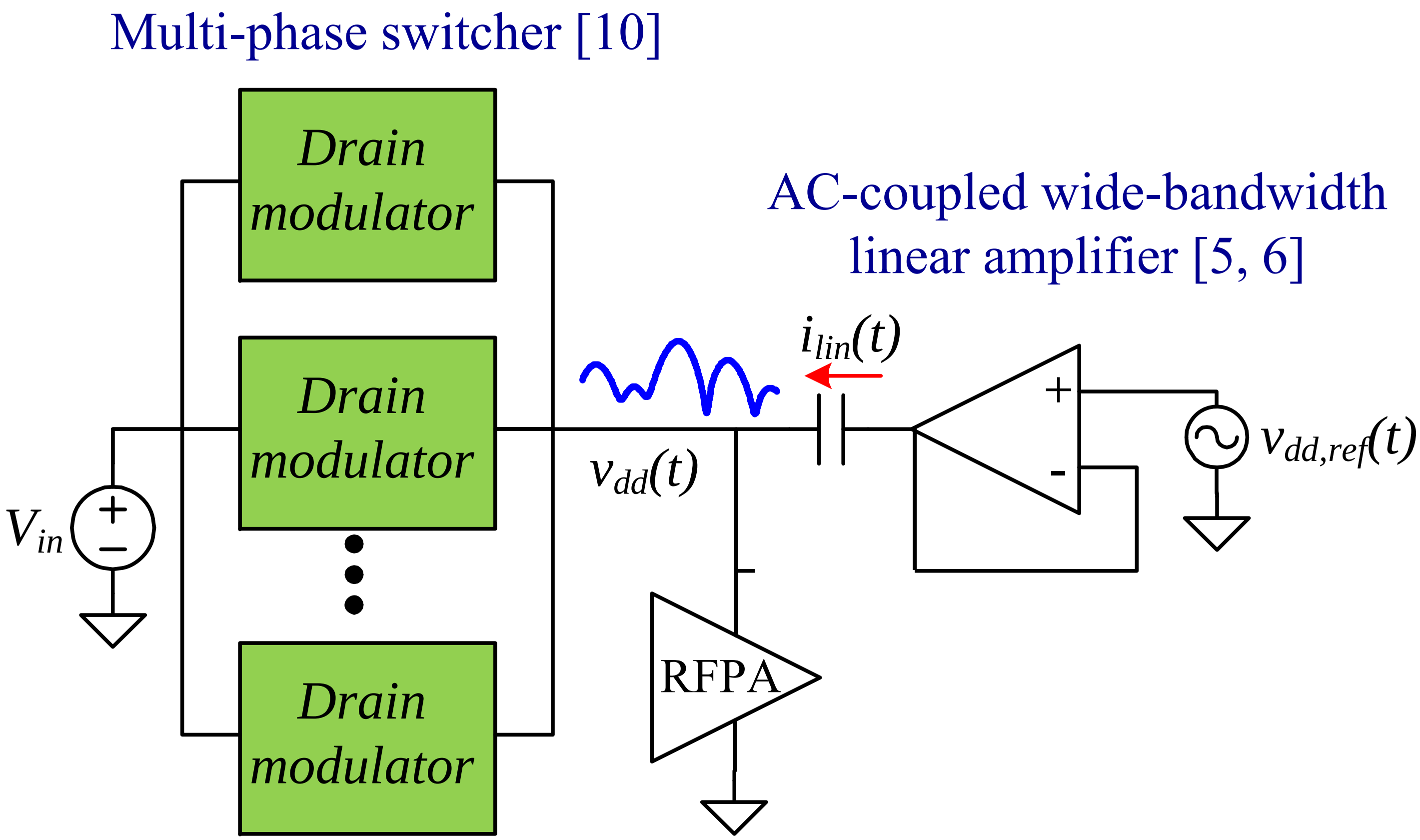
Envelope tracking experimental results



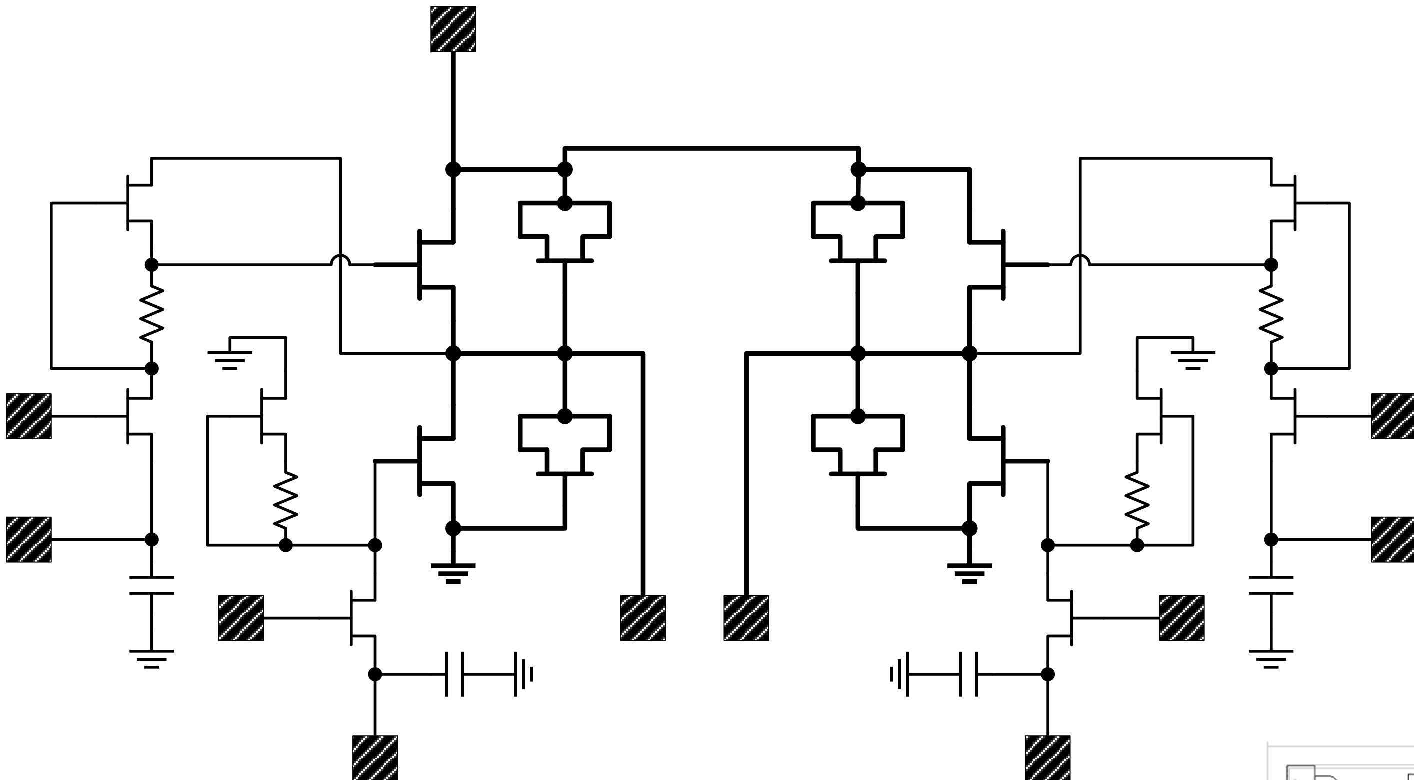


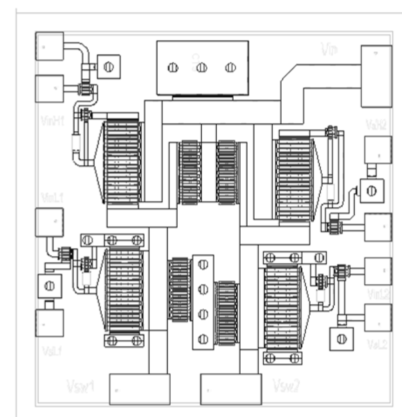
- 20 MHz LTE envelope, 100 MHz switching frequency
- Power stage efficiency: 83.7%
- Total efficiency: 80.1% (including on-chip driver loss)
- Normalized RMS error: 5.4%

Path to very high bandwidth (500MHz) tracking



Two-phase buck converter chip



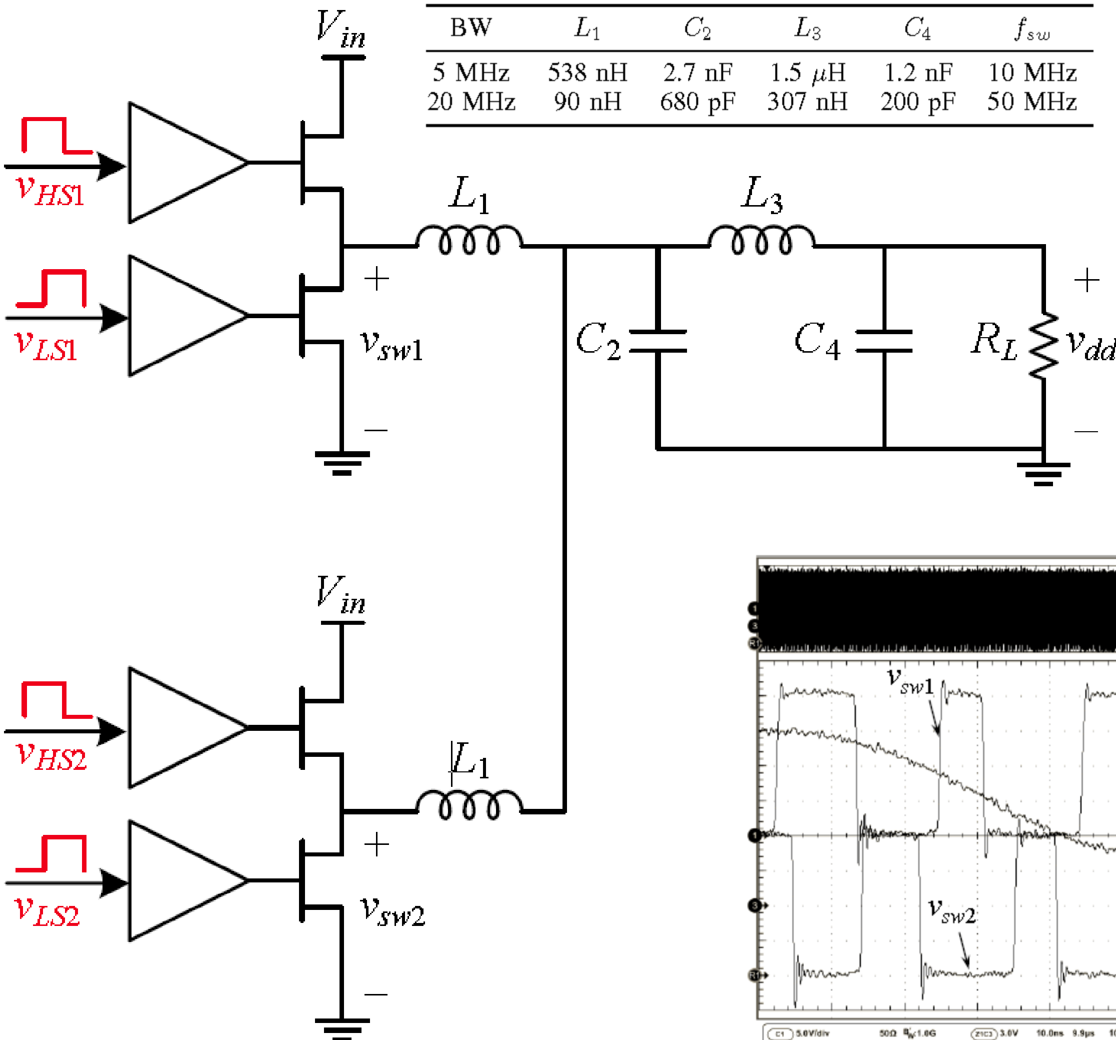


2.6 x 2.7 mm

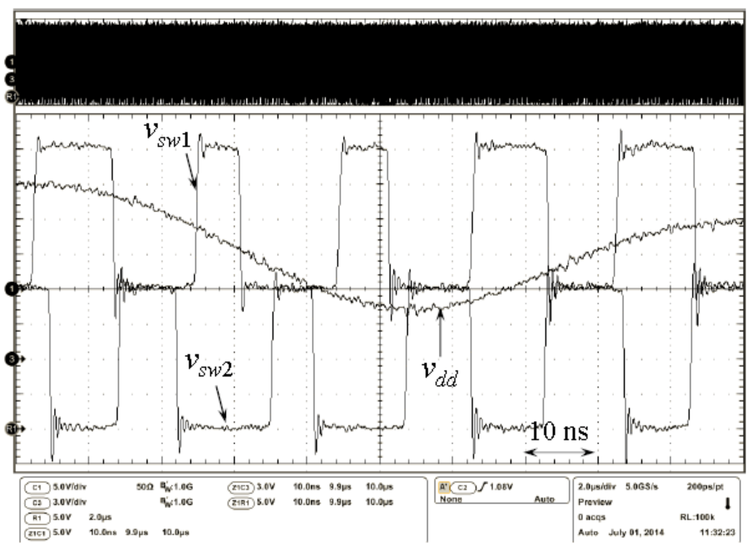
Two-phase switching ET amplifier

FOURTH-ORDER FILTER DESIGNS FOR TWO PHASE CONVERTERS.

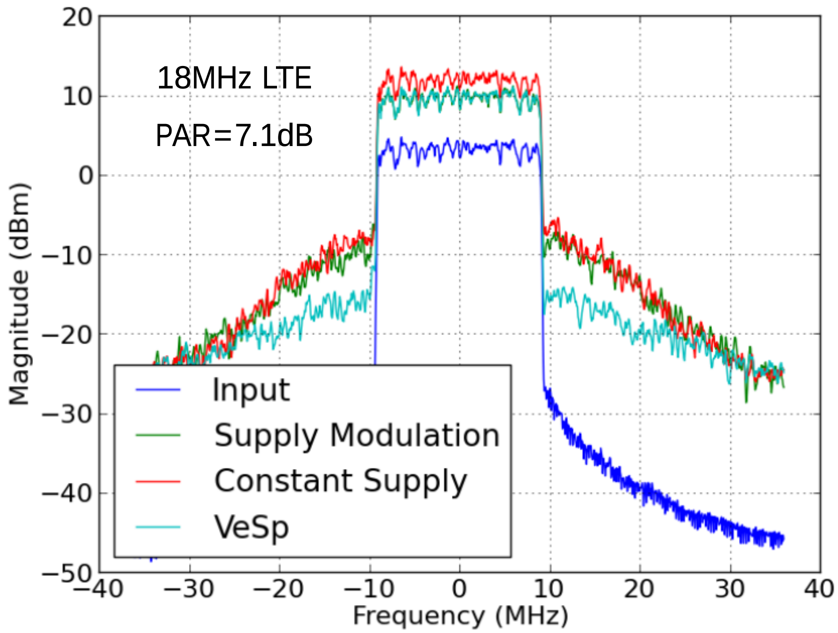
BW	L_1	C_2	L_3	C_4	f_{sw}
5 MHz	538 nH	2.7 nF	1.5 μH	1.2 nF	10 MHz
20 MHz	90 nH	680 pF	307 nH	200 pF	50 MHz

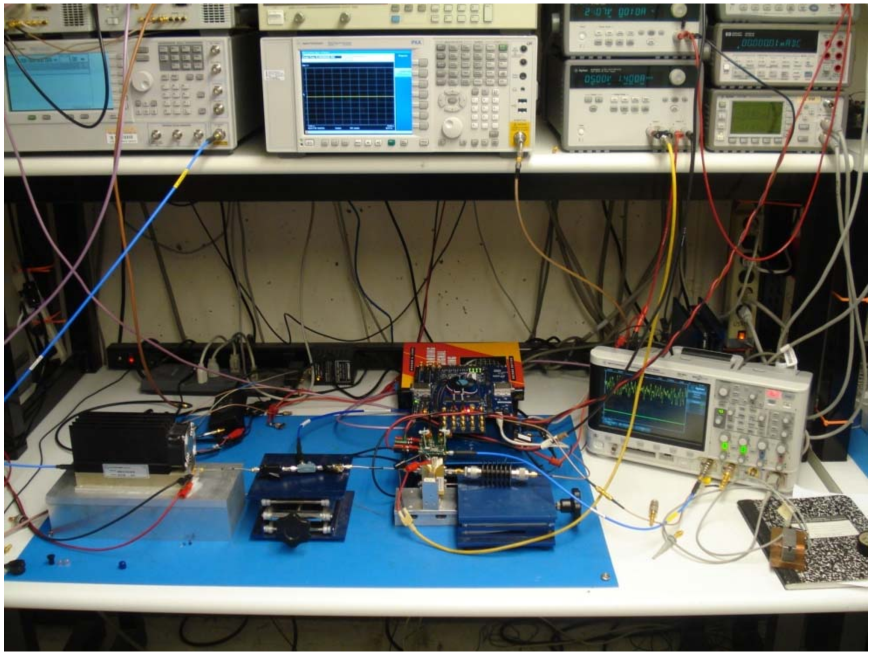


- 50MHz per-phase switching frequency
- 25MHz tracking bandwidth
- 3.4% RMSE tracking 20MHz LTE envelope
- **93.2% peak, 85% total efficiency**



ET Transmitter System Test Results





VeSP = signal split + DPD

Composite power-added efficiency: 53.6%

ACPR: -28 dB

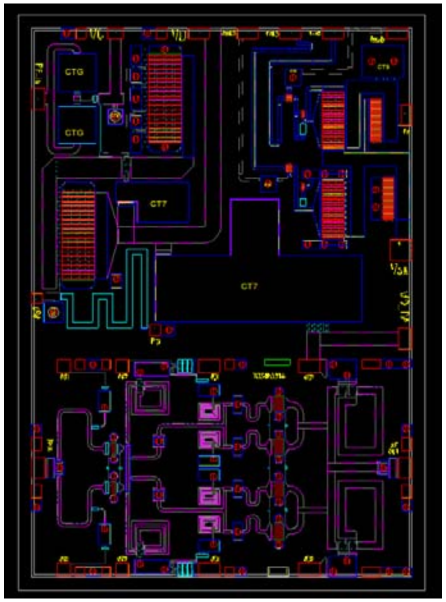
Conclusions

- Integrated switching converters in GaN-on-SiC process
- 20 V, 10 W peak, >90% peak efficiency, 100 MHz switching
- Accurate tracking of 20 MHz LTE envelope, 85% overall efficiency
- Path to ET RF transmitter SOC integration with up to 500 MHz envelope bandwidth capability in GaN-on-SiC process

ET Transmitter on a Chip

5.4 x 3.8 mm in GaN-on-SiC RF process

Cascode ET amp, 500 MHz BW [5, 6]



100MHz switching ET amp, 20MHz BW [8, 9]

10W, X-Band RFPA [2, 3, 4]

Acknowledgments

- Dr. Chuck Campbell, John Hitt and Maureen Kalinski, TriQuint (now Qorvo)
- DARPA MPC program

Selected References

[1] J. Hoversten, S. Schafer, M. Roberg, M. Norris, D. Maksimovic, Z. Popovic, "Co-design of PA, Supply and Signal Processing for Linear Supply-Modulated RF Transmitters," *IEEE Trans. Microwave Theory and Techniques, Special Issue on PAs,* pp. 210-220, April 2012.

[2] M. Litchfield, M. Roberg, Z. Popovic, "A MMIC/hybrid high-efficiency X-band power amplifier, *Power Amplifiers for Wireless and Radio Appl. (PAWR), 2013 IEEE Topical Conf.*, pp.10,12, Jan. 2013.

[3] S. Schafer, M. Litchfield, A. Zai, C. Campbell, Z. Popovic, "X-Band MMIC GaN Power Amplifiers Designed for High-Efficiency Supply-Modulated Transmitters," *IEEE MTT IMS 2013,* Seattle, WA, June 2013.

[4] A. Zai, S. Schafer, D. Sardin, Y. Zhang, D. Maksimovic, Z. Popovic, "High-Efficiency X-Band MMIC GaN Power Amplifiers with Supply Modulation," IEEE IMS 2014

[5] D. Sardin, Z. Popovic, "Decade Bandwidth High-Efficiency GaN VHF/UHF Power Amplifier," *IEEE MTT IMS 2013,* Seattle, WA, June 2013

[6] D. Sardin, Z. Popovic, "High Efficiency 15-500MHz Wideband Cascode GaN HEMT MMIC Amplifiers," IEEE IMS 2014.

[7] M. Rodriguez, Y. Zhang, and D. Maksimovic, "High-frequency PWM buck converters using GaN-on-SiC HEMTs," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2462–2473, 2014.

[8] Y. Zhang, M. Rodriguez, and D. Maksimovic, "High-frequency integrated gate drivers for half-bridge GaN power stage," in Control and Modeling for Power Electron. (COMPEL), 2014 IEEE 15th Workshop on, 2014.

[9] Y. Zhang, M. Rodriguez, and D. Maksimovic, "100 MHz, 20 V, 90% efficient synchronous Buck converter with integrated gate driver," *in Proc. IEEE Energy Convers. Congr. Expo.*, 2014.

[10] M. Norris, D. Maksimovic, "10 MHz large signal bandwidth, 95% efficient power supply for 3G-4G cell phone base stations," IEEE APEC 2012.