Monolithic Very High Frequency GaN Switched-Mode Power Converters

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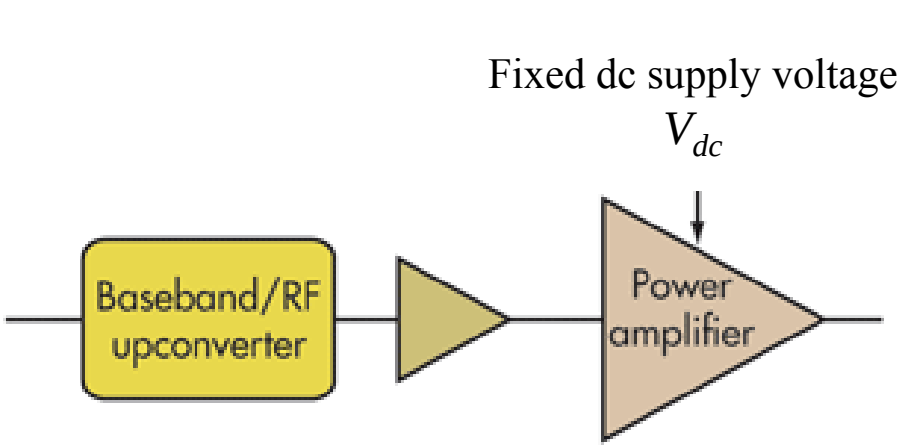
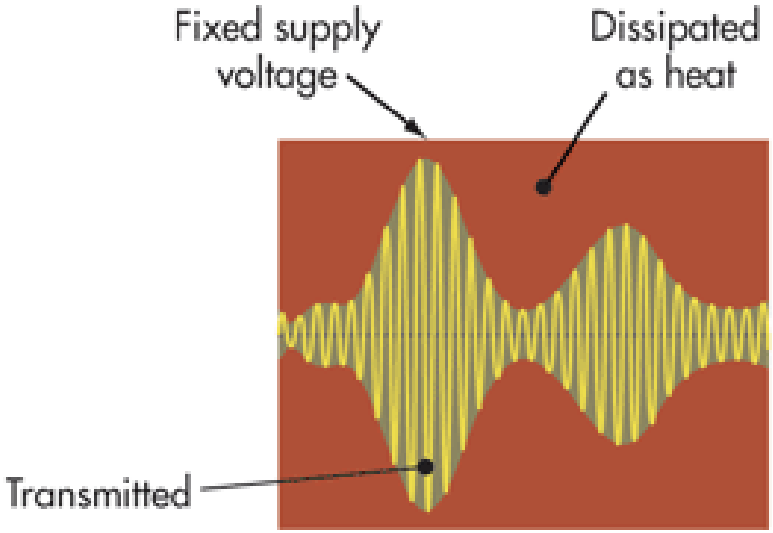
Application of interest: RF transmitters

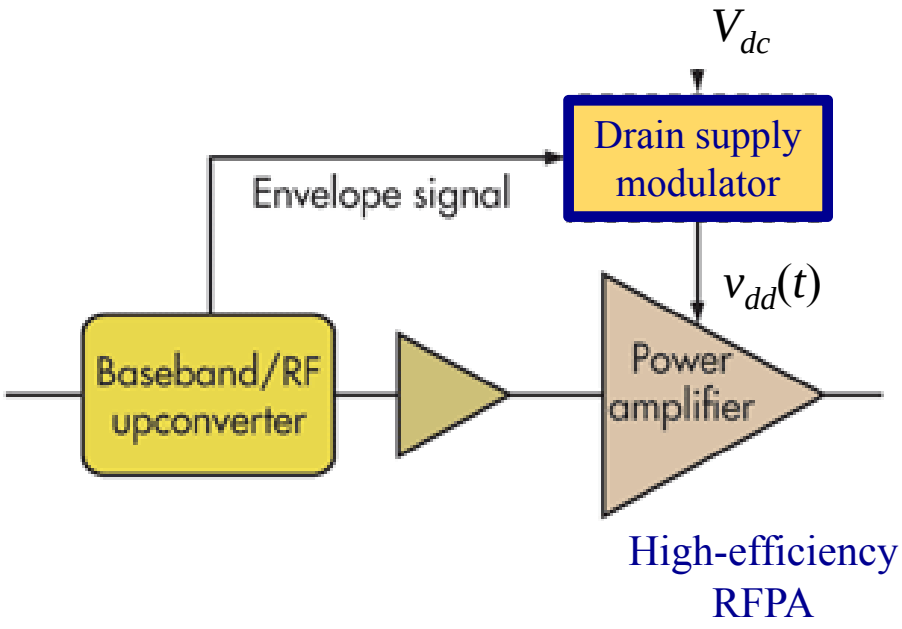




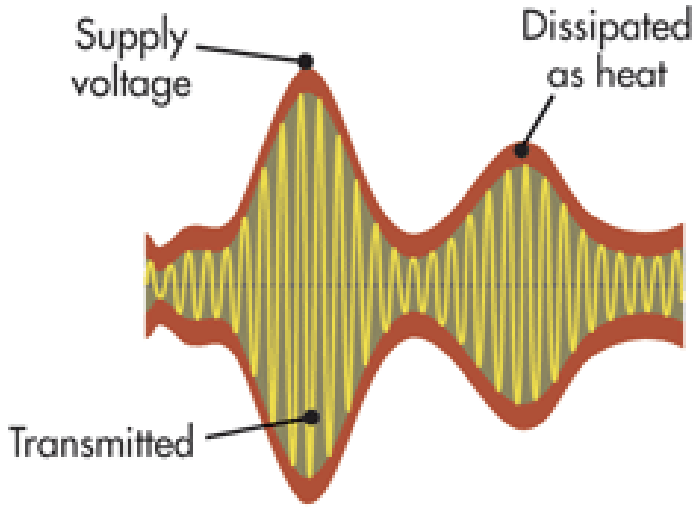
Problem: low efficiency of conventional RF transmitters in mobile, base station, and other wireless infrastructure systems

- High peak-to-average ratio (PAR) signals
- Continuous-wave (CW) or low-PAR signals at average power levels below peak

Objective: high-efficiency, flexible RF transmitters



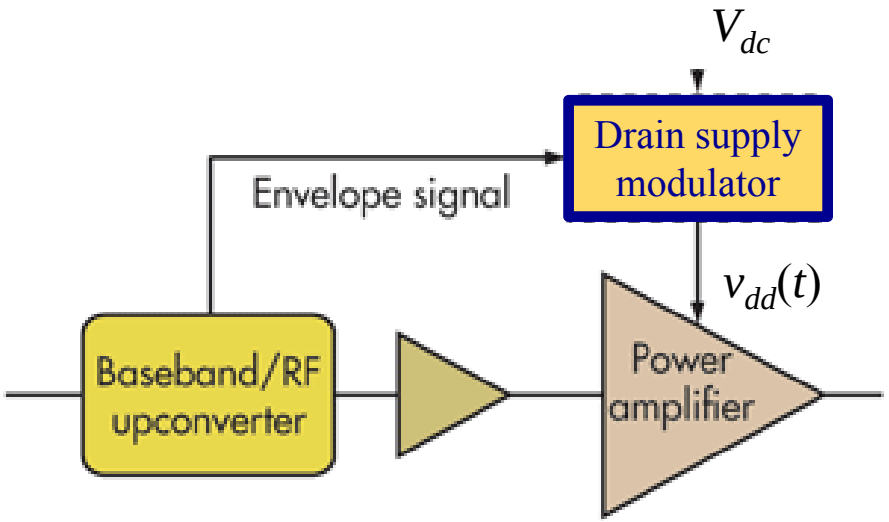
High-efficiency RFPA



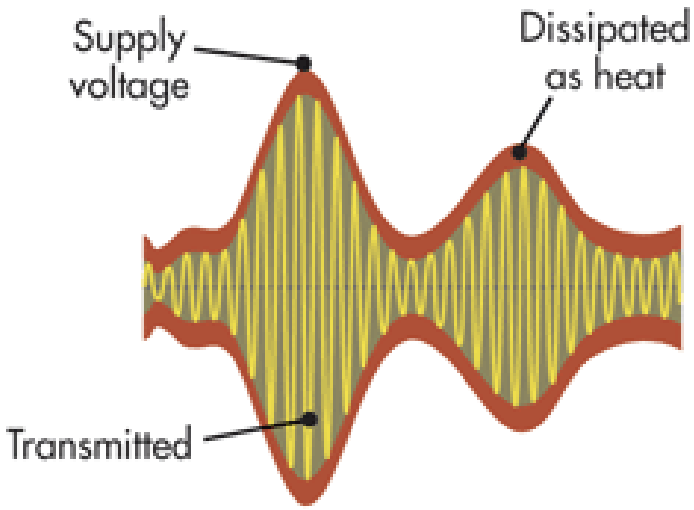
One possible system efficiency improvement approach:
"envelope tracking" transmitters based on drain supply modulation

- High-efficiency RFPA
- High-efficiency, wide-bandwidth envelope-tracking drain supply modulator
- System co-design and integration

Objective: high-efficiency, flexible RF transmitters



High-efficiency RFPA



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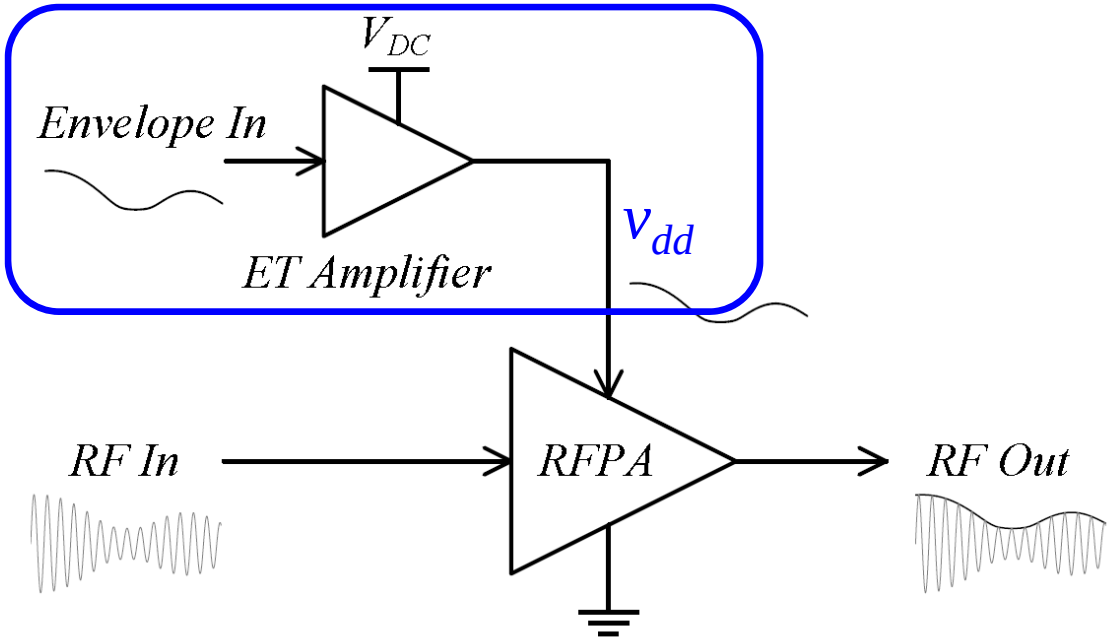
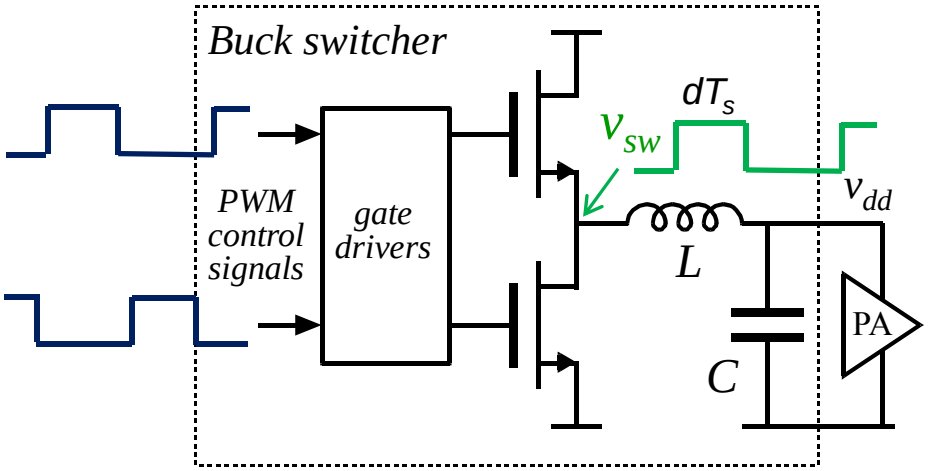
- High-efficiency RFPA
- **High-efficiency, wide-bandwidth envelope-tracking drain supply modulator**
- System co-design and integration

Drain supply modulator design challenges

- Wide tracking bandwidth [$BW_{tracking}$ = 10's to 100's of MHz]
- High slew rate [dv_{dd}/dt = several V/ns]
- High efficiency to realize system-level efficiency improvements



Basic approach: PWM buck dc-dc converter



LC filter corner frequency

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

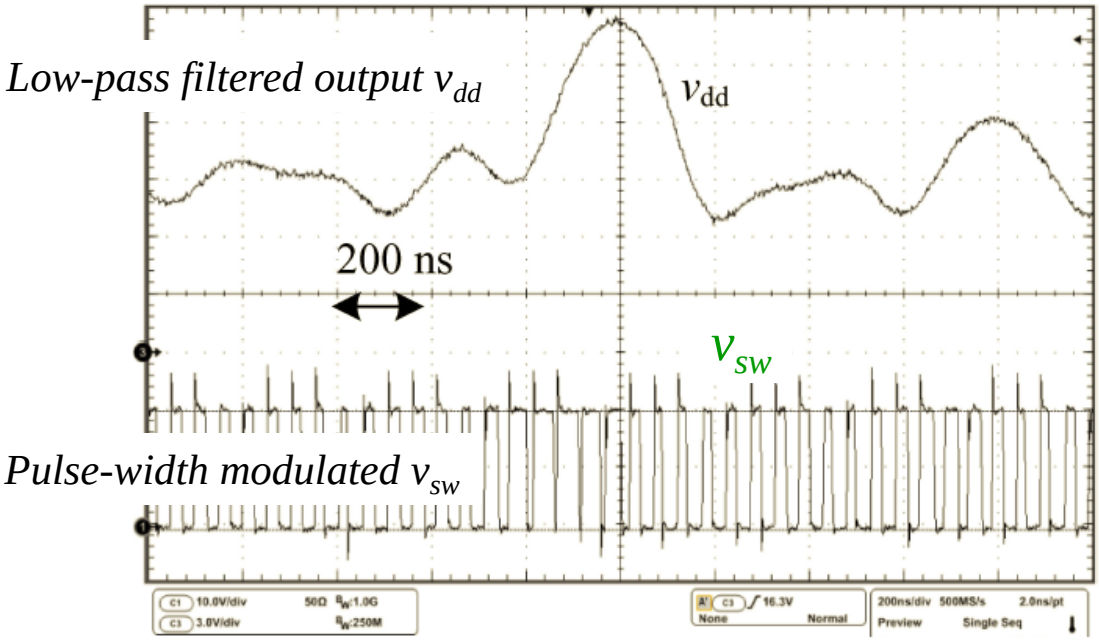
$$f_o > BW_{tracking}$$

Filtered output voltage

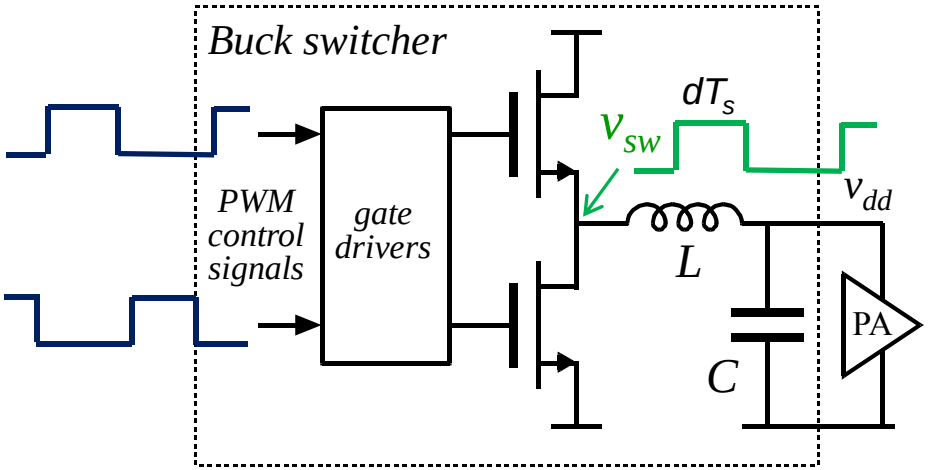
$$v_{dd}(t) \approx d(t)V_{in}$$

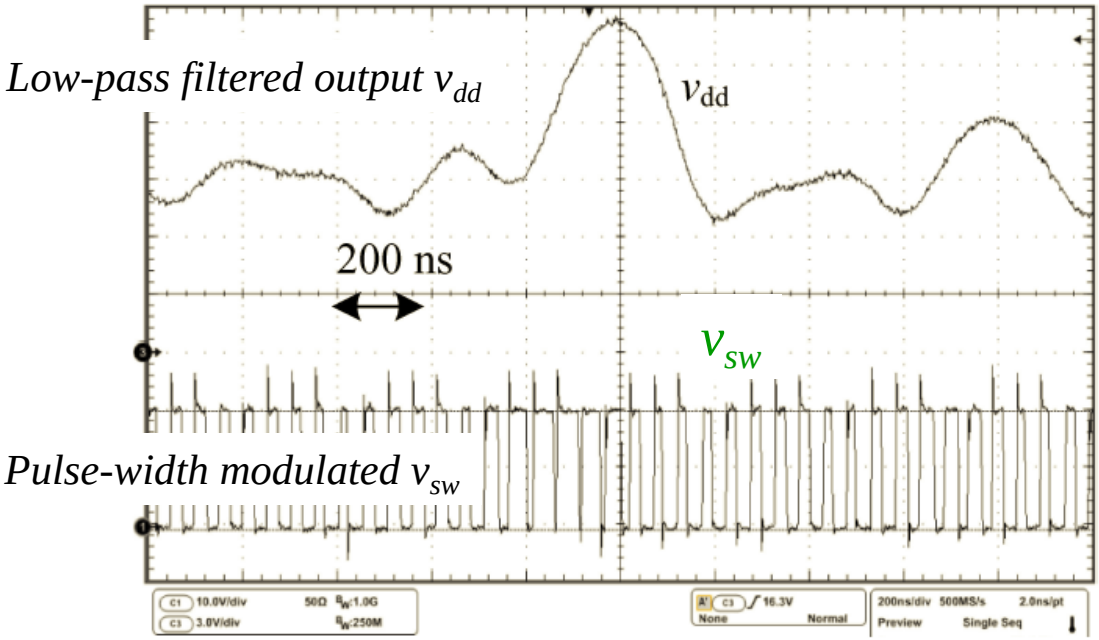
Switching frequency requirement

$$f_s >> BW_{tracking}$$



Challenge: high-efficiency at high switching frequency





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Switching frequency requirement

$$f_s >> BW_{tracking}$$

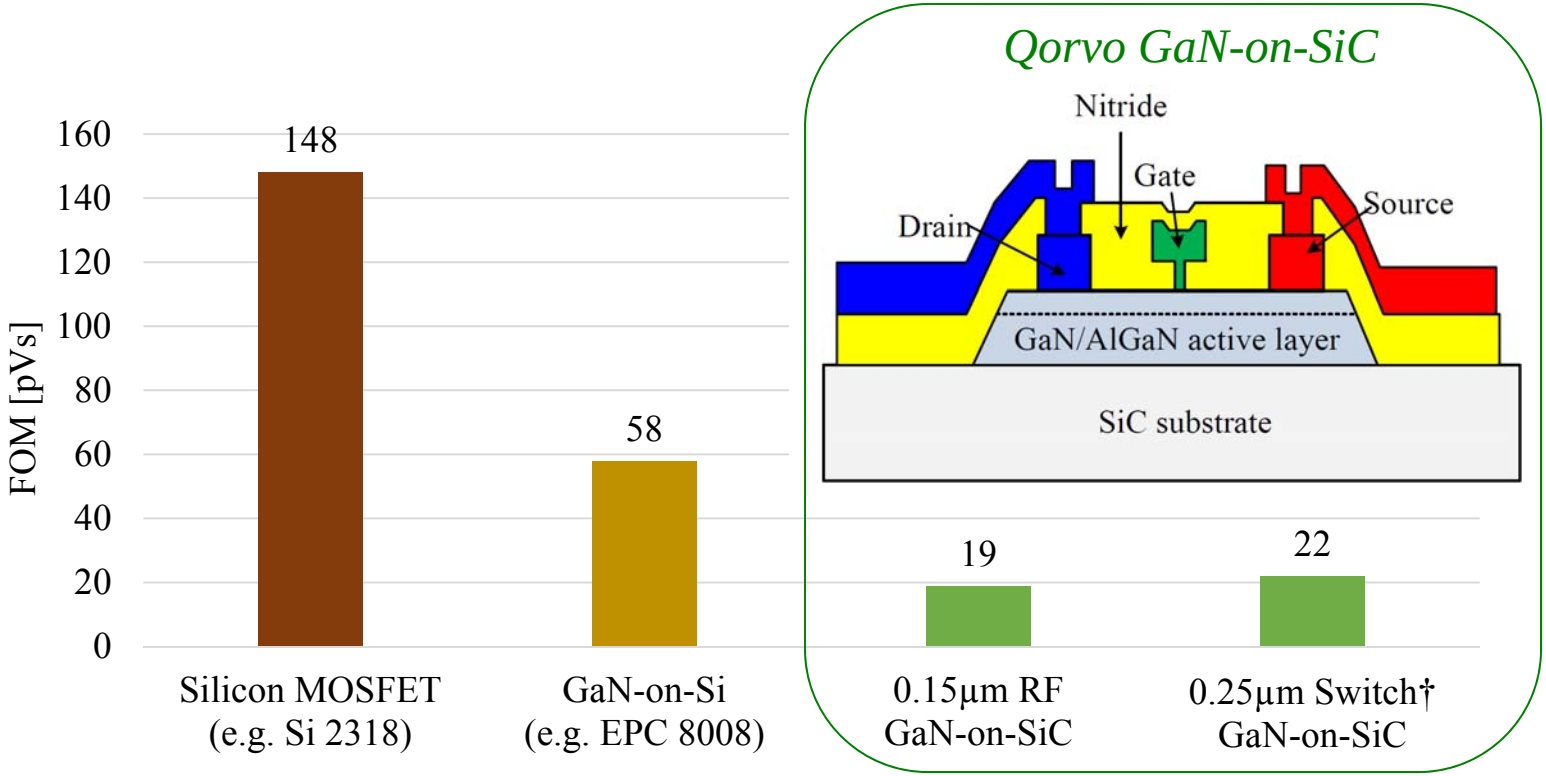
Conventional switched-mode power converter designs are limited to low switching frequencies (MHz) due to switching losses proportional to f_s

Approach: monolithic VHF GaN switchers

Switched-mode converter design techniques in GaN process

- Gate-drive integration
  - Enables efficient PWM of high-bridge power stage at VHF
  - Enables logic-level inputs to monolithic GaN switcher chip
- Zero-voltage switching
  - Reduces switching losses
- Multi-phase conversion
  - Improves tracking bandwidth to switching frequency ratio
  - Enables power scaling
  - Reduces ripple

GaN-on-SiC process: switch FOM = $R_{on,s}Q_{g,s}$

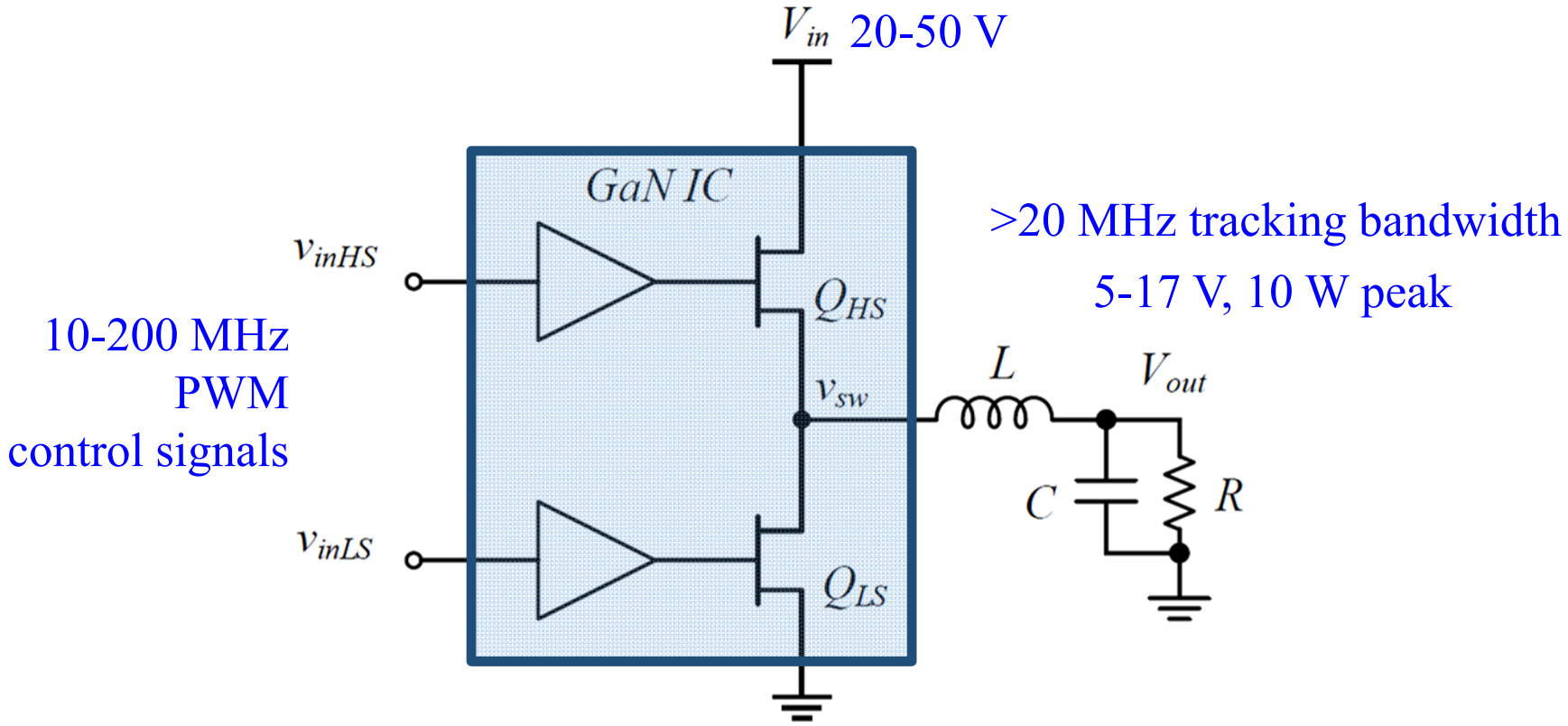


Superior figure of merit allows switched-mode converter circuit design techniques leading to high efficiencies at very high switching frequencies

Integrated converter circuits tested at 10-200 MHz switching frequencies, up to 20V in the 0.15µ RF process, and up to 50V in the 0.25µ Switch process

NMOS-only process: circuit design challenges

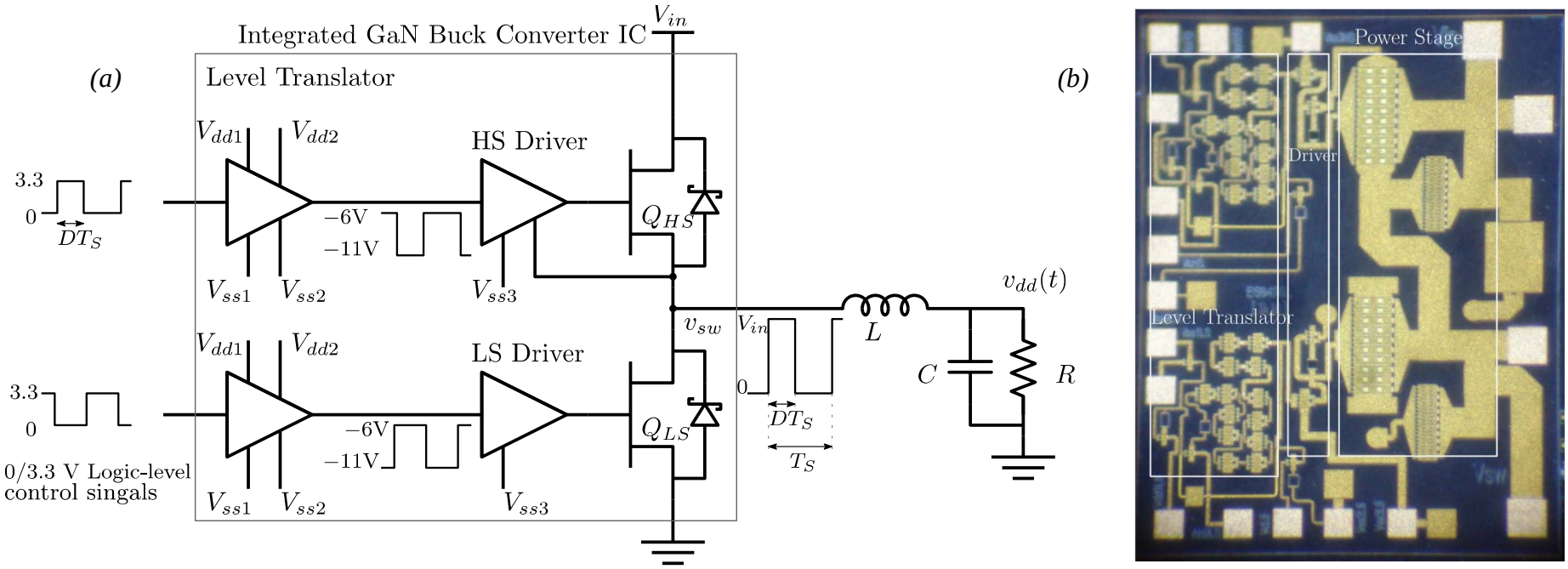
10-200 MHz Monolithic GaN PWM Buck Converters



Key circuit innovations

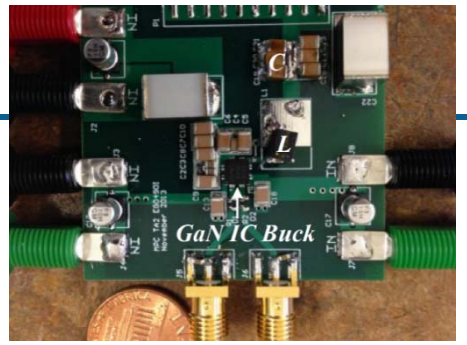
- Integrated high-side gate driver in D-mode n-channel-only GaN process to support very high frequency PWM control
- Integrated level translators in D-mode n-channel-only GaN process to allow standard logic-level PWM control inputs

Monolithic GaN half-bridge switcher

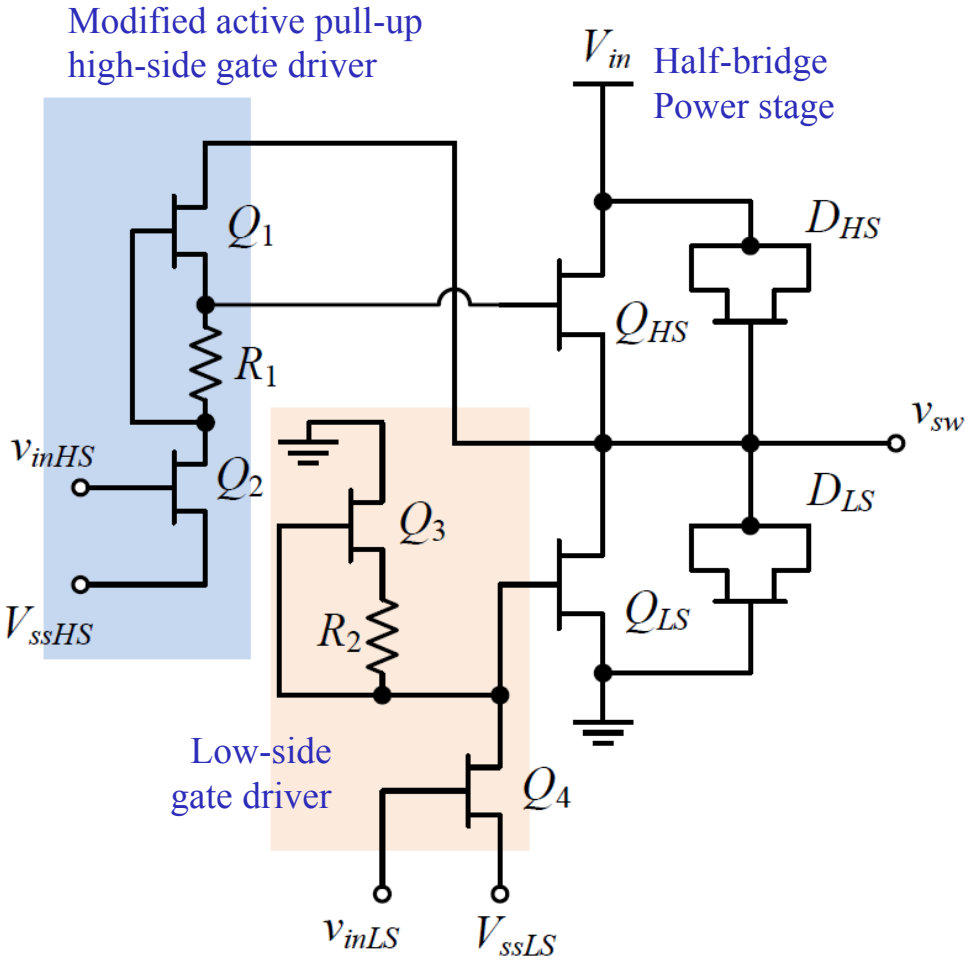


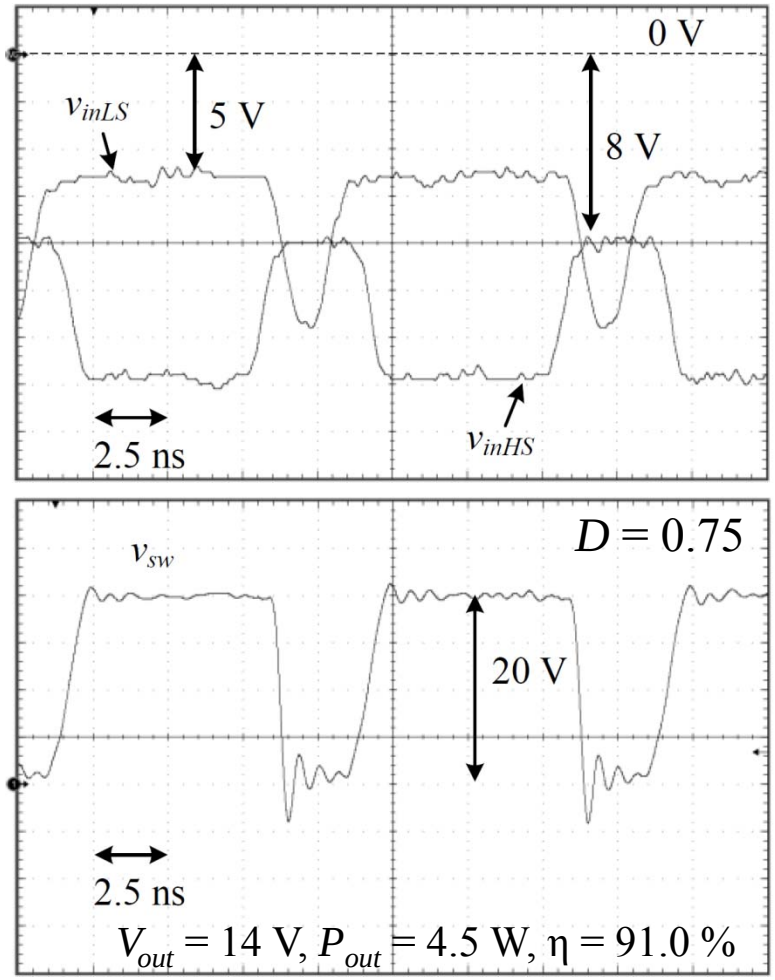
- Integrated half-bridge power stage, low-side and high-side gate drivers, and control signal level translators
- V_{in} up to 25V, P_{out} up to 10W, up to 200 MHz switching frequency
- 2.4 x 3.1 mm die in 0.15µm GaN process

Gate-driver integration



100 MHz switching waveforms



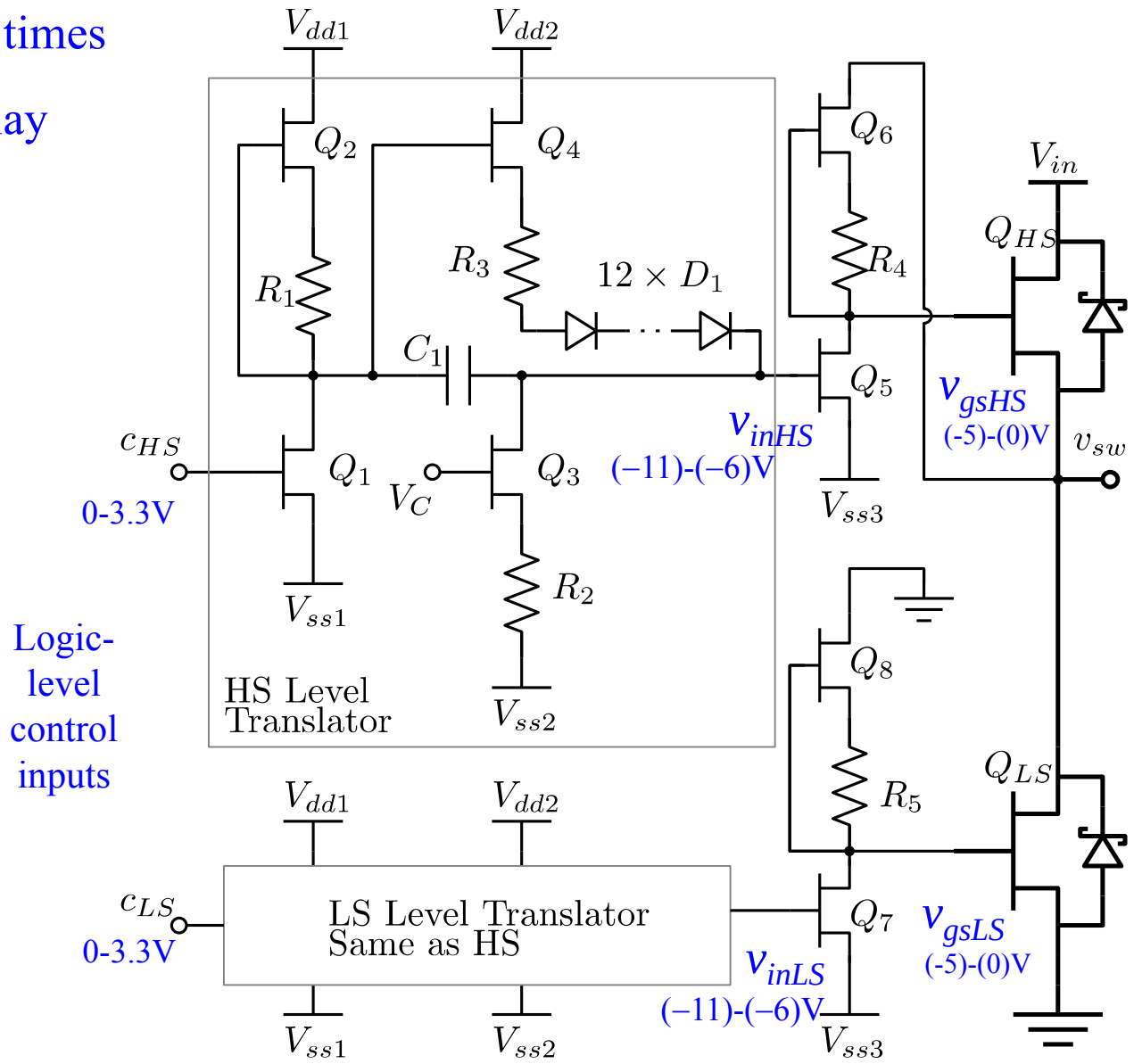


Modified active pull-up high side driver

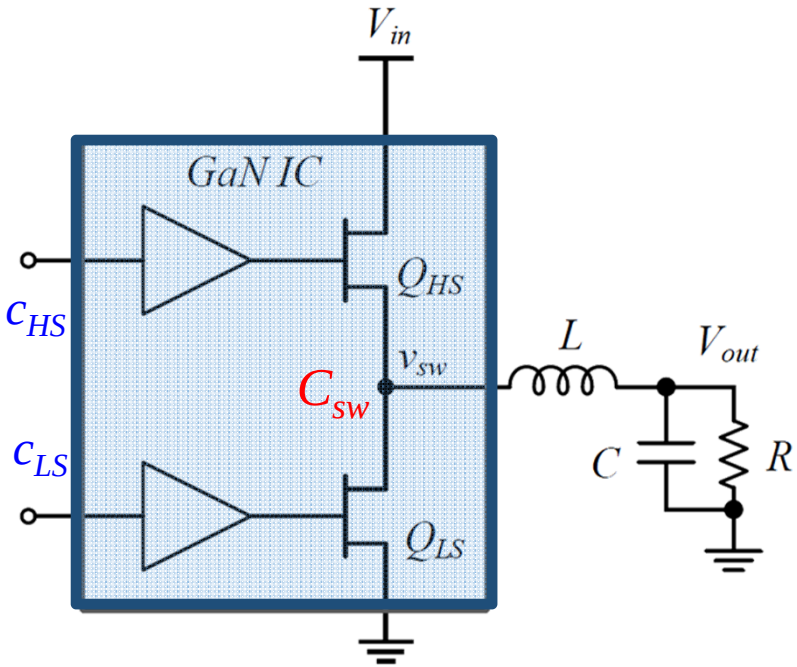
- Pull-up Q_1 drain tied to v_{sw}, reduced loss
- <0.2W total driver loss at 20V, 100 MHz

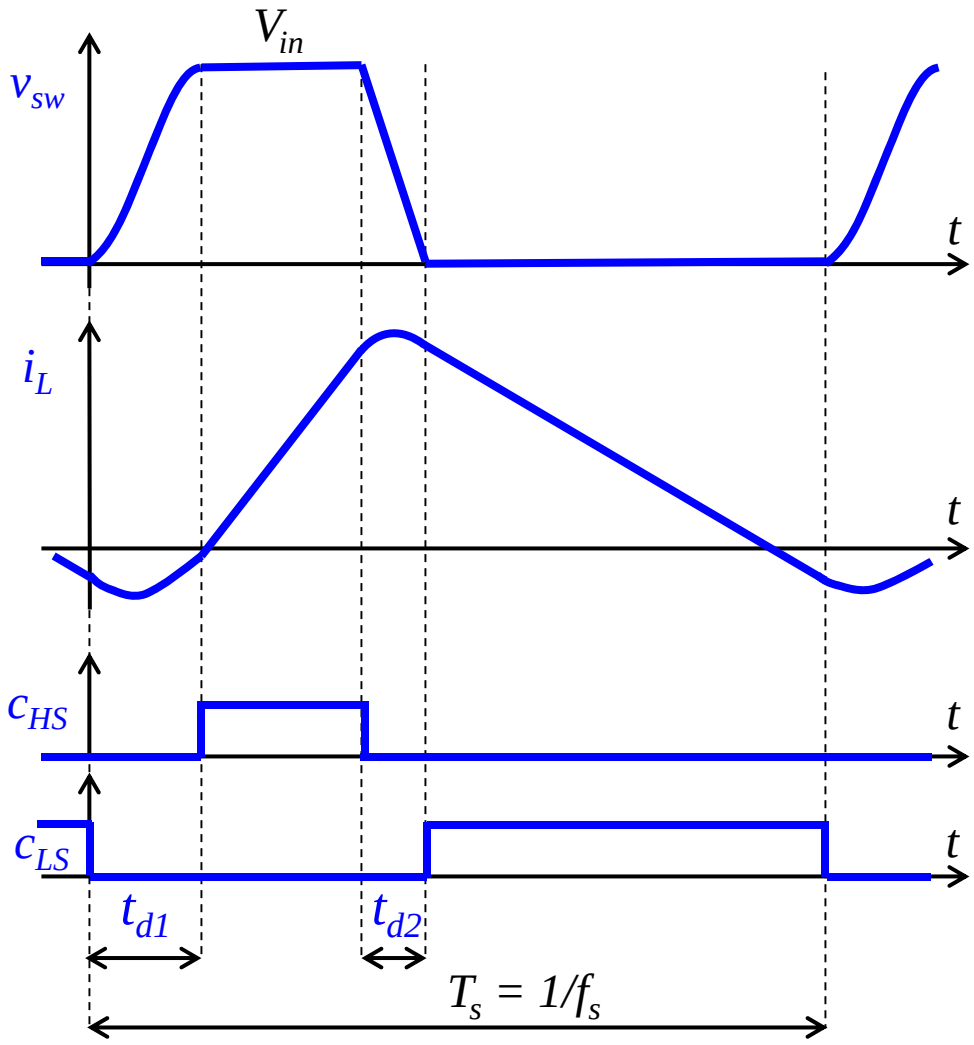
Integrated level translators

- < 1ns v_{gs} rise and fall times
- < 1ns propagation delay
- 14 mW loss in level translators



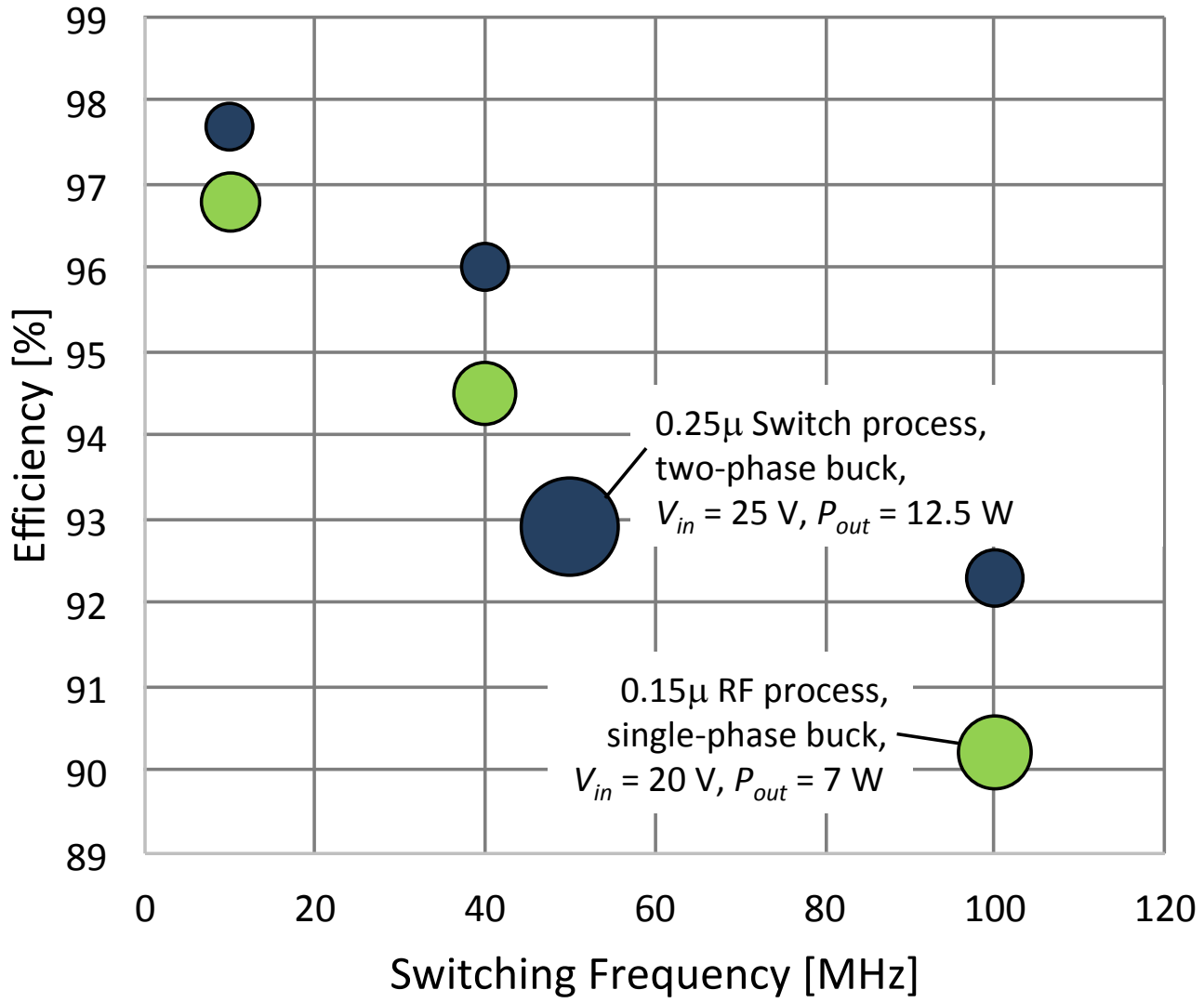
Zero-voltage-switching (ZVS) operation





- L-C_{sw} resonant ZVS transitions
- Much reduced switching losses
- Dynamically adjusted dead-times t_{d1}, t_{d2}

Experimental results: efficiency versus sw. frequency



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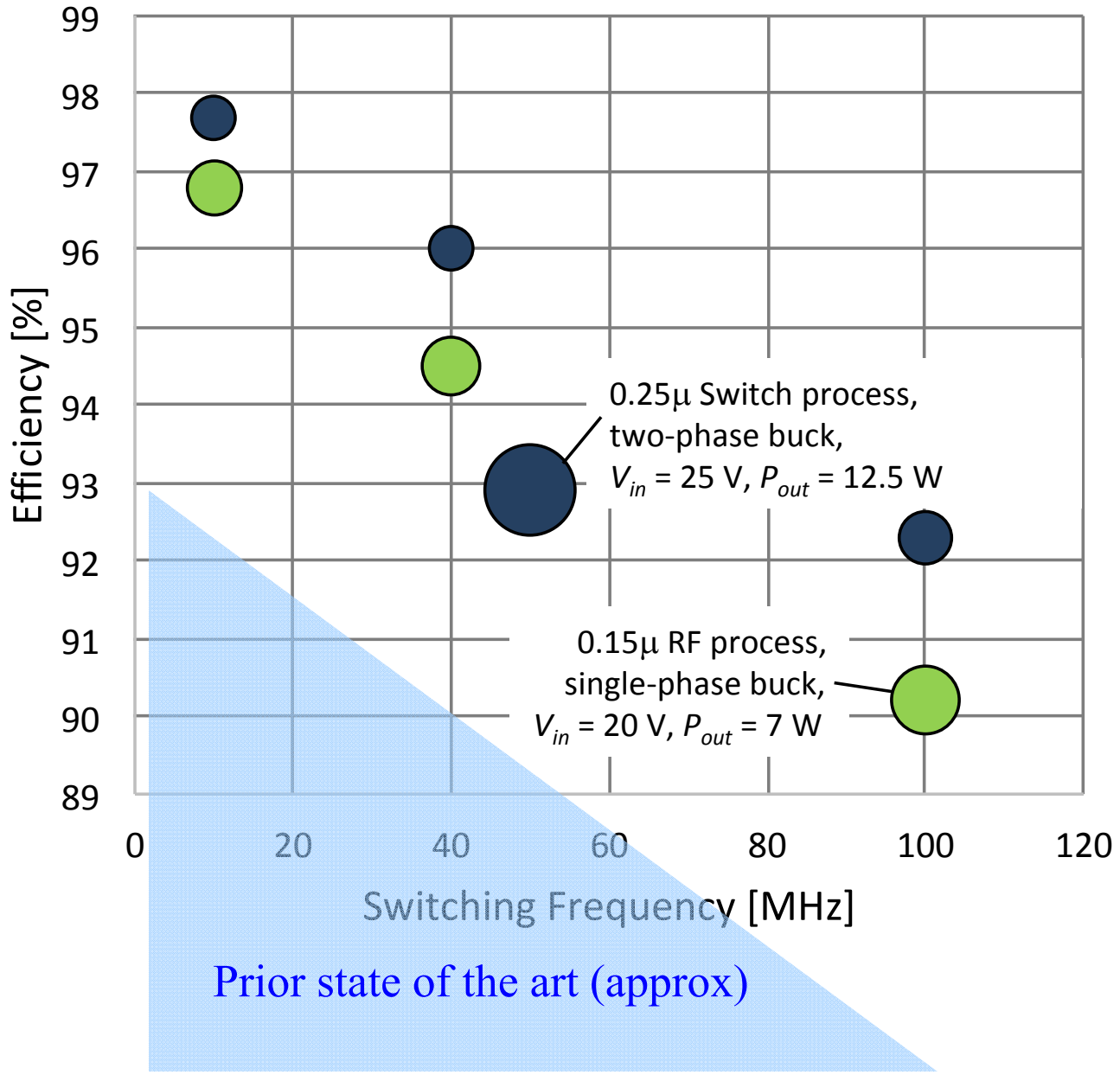
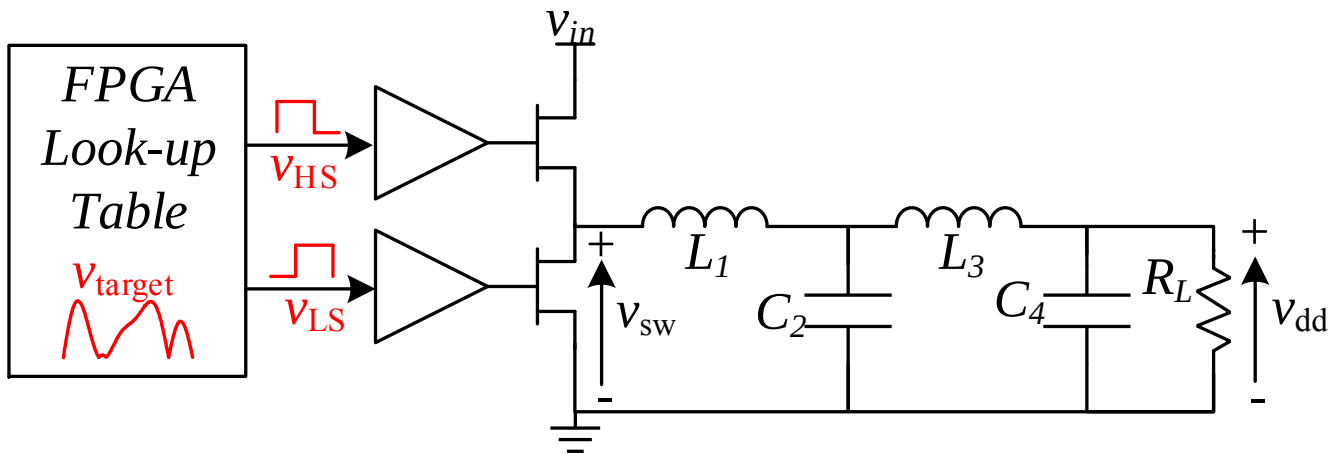


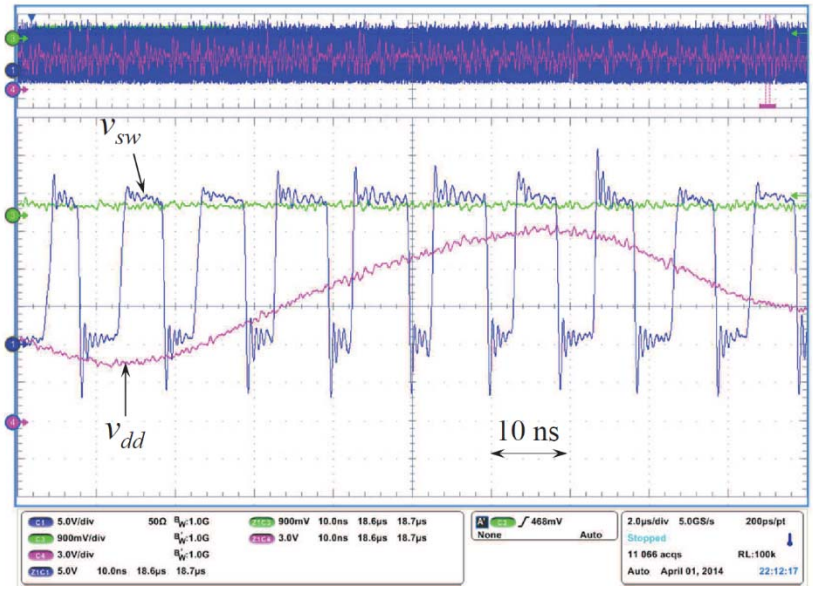
Application: envelope tracking supply for RFPAs

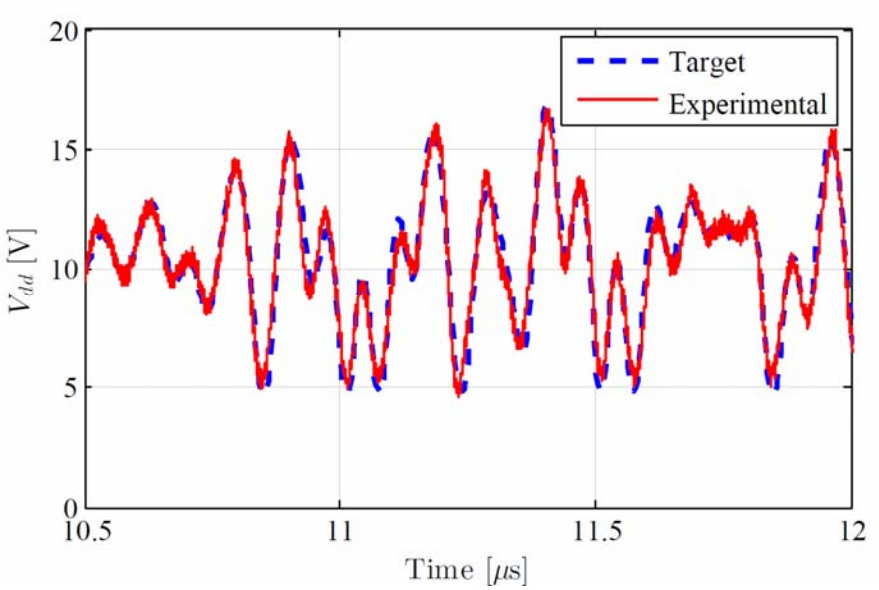
- Target signal: 20 MHz bandwidth LTE envelope
- 4th order filter, 25 MHz cut-off frequency
- 100 MHz switching frequency



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

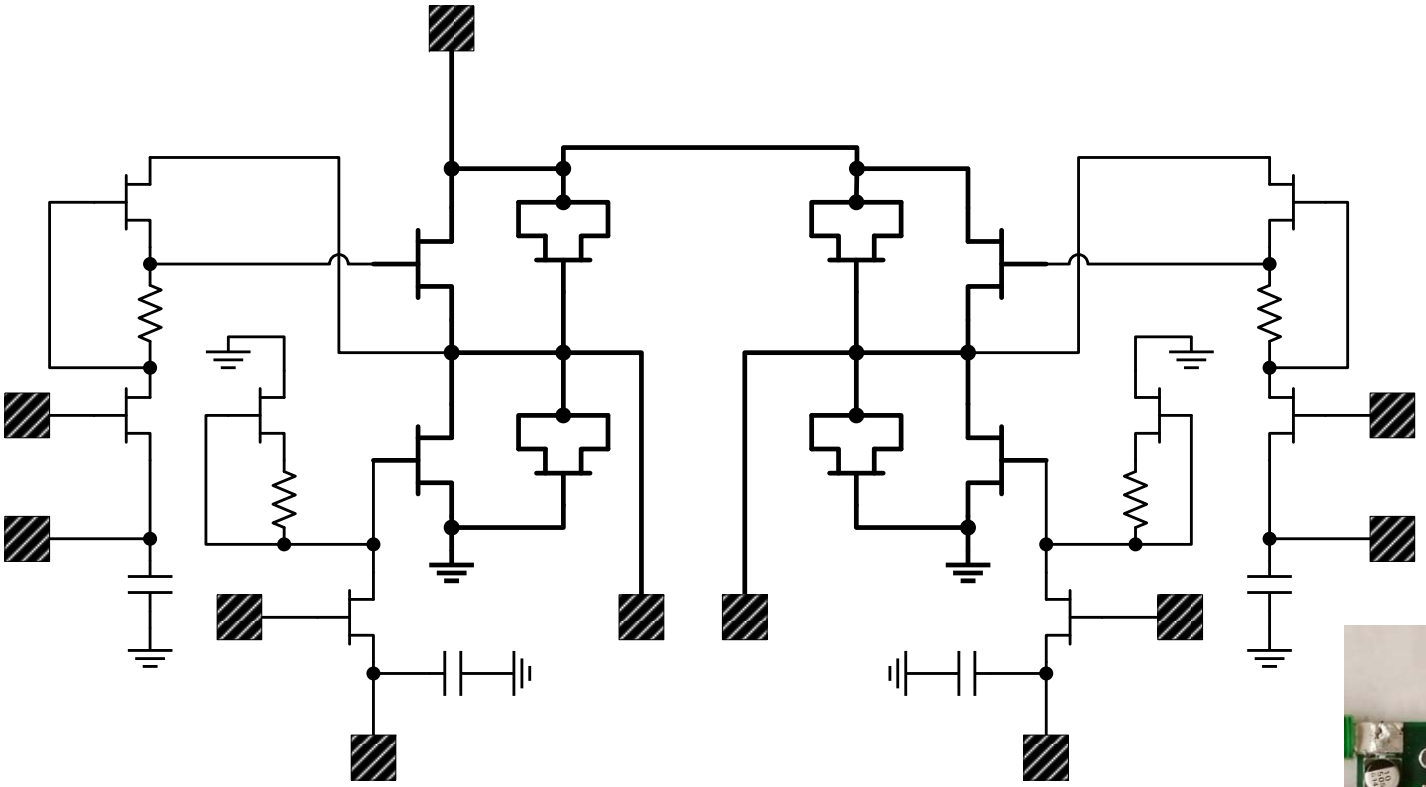
Envelope tracking experimental results

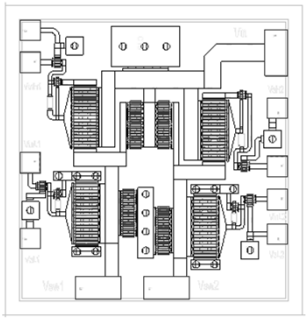




- 20 MHz LTE envelope, 100 MHz switching frequency
- Power stage efficiency: 83.7%
- Total efficiency: 80.1% (including on-chip driver loss)
- Normalized RMS error: 5.4%

Monolithic two-phase GaN buck converter chip





2.6 x 2.7 mm

0.25μ GaN-on-SiC switch process

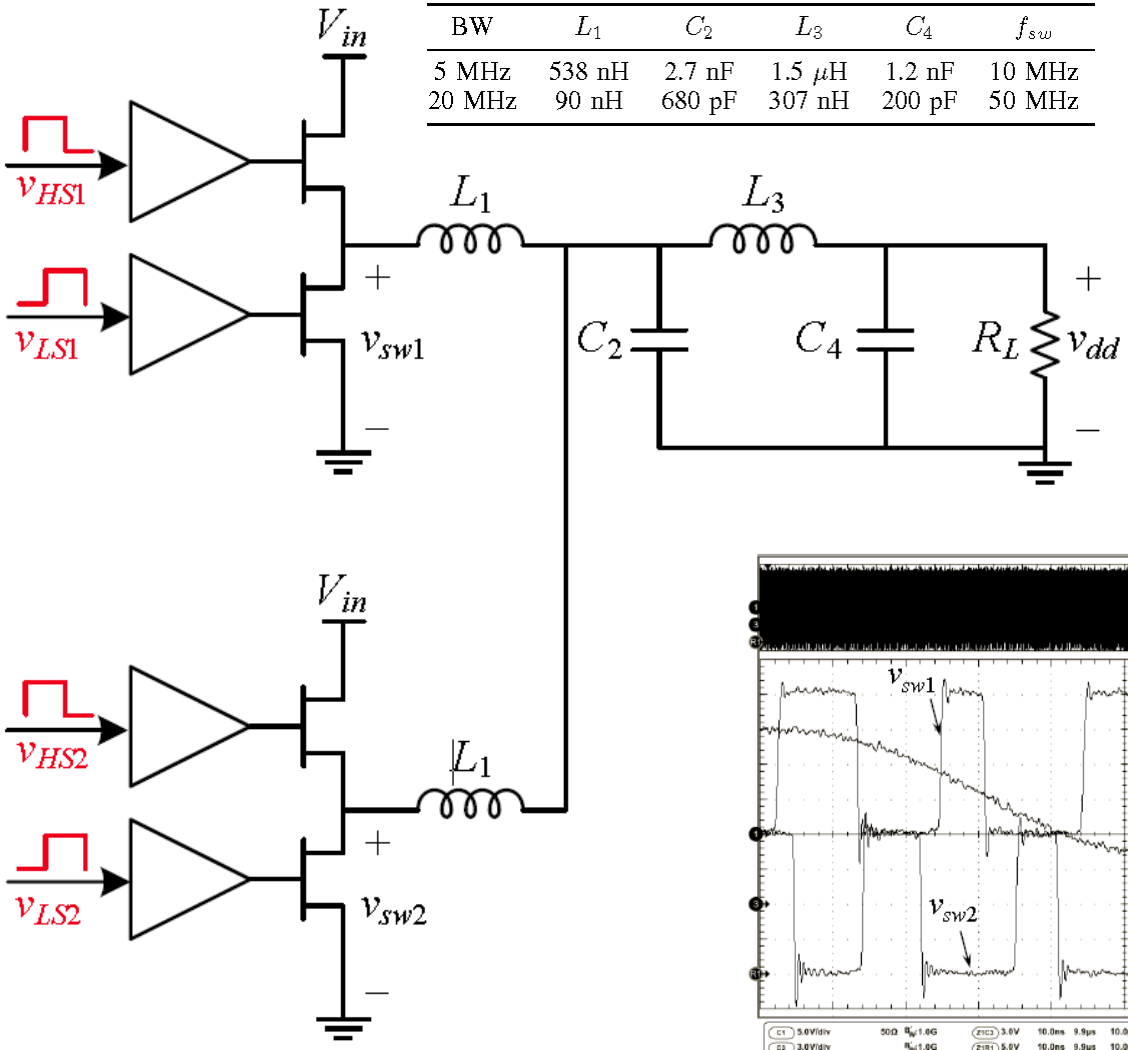
20-pin QFN package

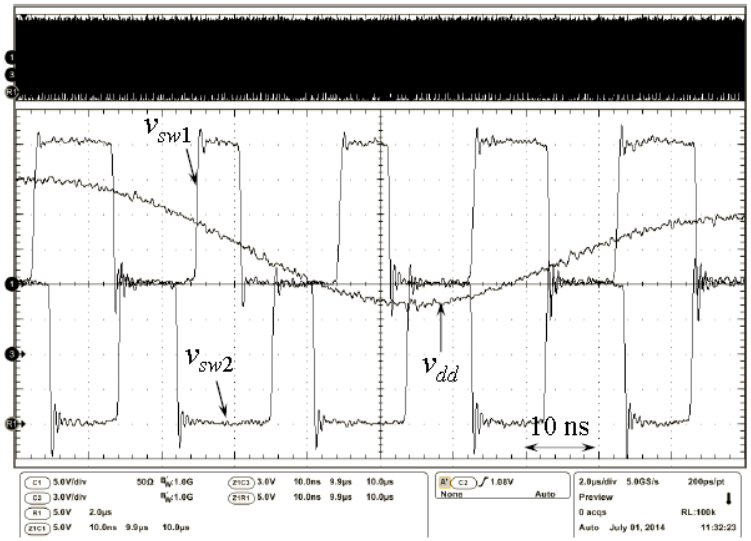
Air-core inductors

Two-phase switching drain supply modulator

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





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

System integration: X-Band PA with drain supply modulation

Switcher drive inputs

DC supply

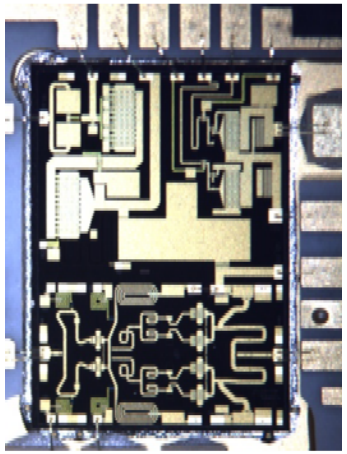
RF VHF/UHF input

DC supply, modulator

X-band input

X-band modulated output

DC supply, PA



5.4 x 3.8 mm MMIC

MMIC carrier board

Conclusions

- GaN processes offer superior switch FOM and enable circuit design techniques leading to very high-efficiency VHF switch-mode power converters
  - Gate-drive integration with level translation
  - Multi-phase zero-voltage switching
- Prototype 10-200 MHz monolithic GaN switchers, 10W, up to 50V
- Future work
  - Companion CMOS chips: generation of auxiliary bias voltages and control functions
  - Scaling to high-voltage processes and higher power levels
- Impact on applications
  - Ultra-high efficiency, flexible RF transmitters
  - Adaptive dc voltage scaling for RF power amplifiers
  - Ultra high power density dc-dc converters
  - Wireless power transfer systems
  - High levels of system integration