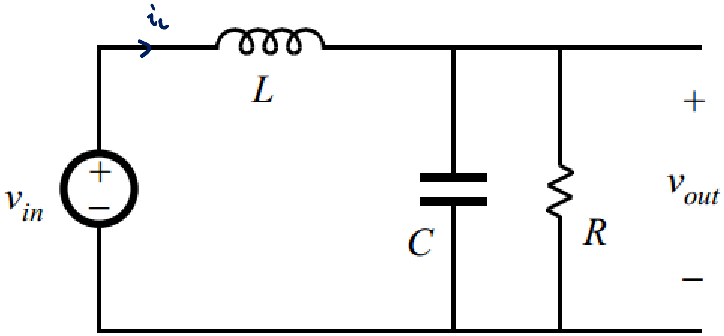
Resonant Circuits

ECE 481

$i_L \approx I_L$
$v_{out} \approx V$ } small ripple approximation (SRA) does not generally apply



L & C → Filter elements: "Large" L & C, SRA applies

L & C → Resonant elements: "small" L & C, SRA doesn't apply

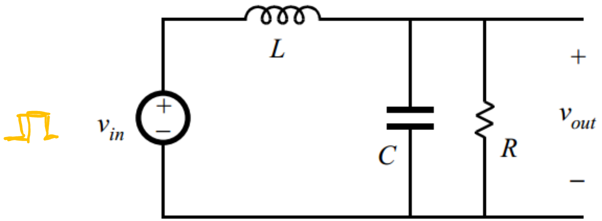
transient analysis

$$LC\frac{d^2 v_{out}}{dt^2} + \frac{L}{R}\frac{dv_{out}}{dt} + (v_{out} - v_{in}) = 0 \quad \& \text{ ICs}$$

{ Diff EQs
Laplace & $\mathcal{L}^{-1}$
Numerical approaches }

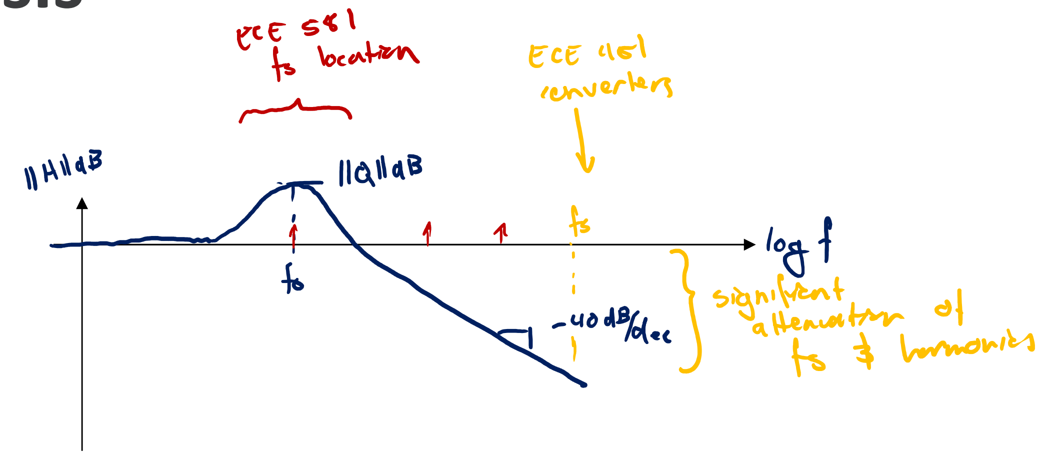
→ techniques from 581

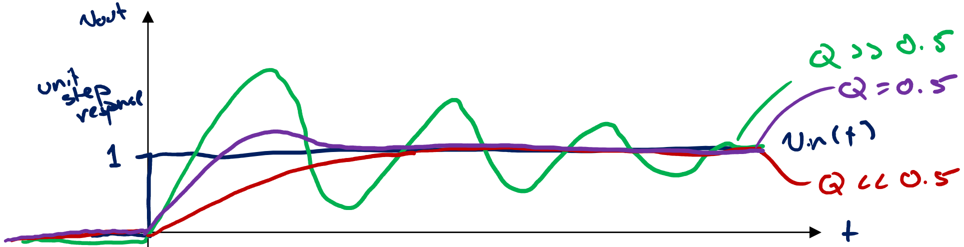
Resonant Circuit Analysis

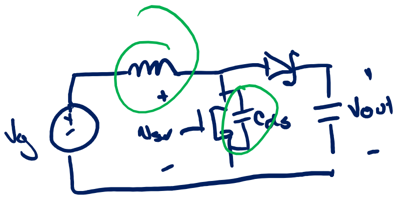


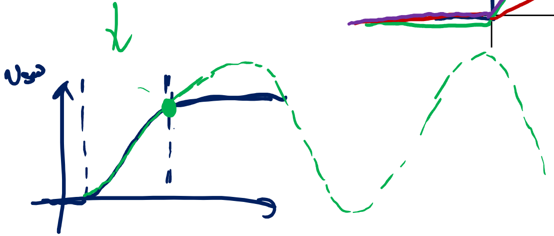
$$\|H(s)\| = \frac{\hat{v}_{out}}{\hat{v}_{in}} = \frac{1}{s^2 LC + s\frac{L}{R} + 1} = \frac{1}{\left(\frac{s}{\omega_0}\right)^2 + \frac{s}{Q\omega_0} + 1}$$

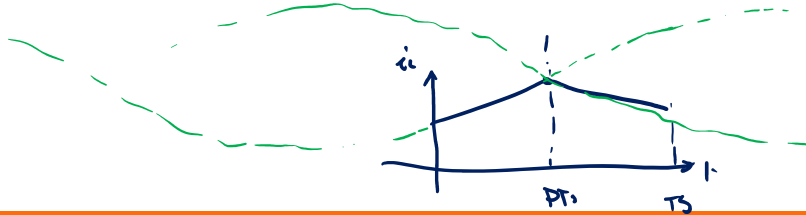
$$\omega_0 = \frac{1}{\sqrt{LC}}, \quad Q = \frac{R}{R_0}, \quad R_0 = \sqrt{L/C}$$









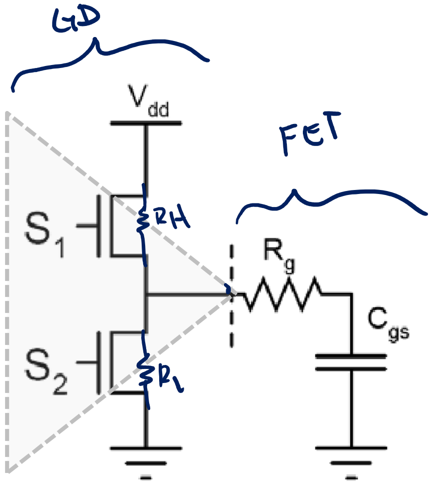


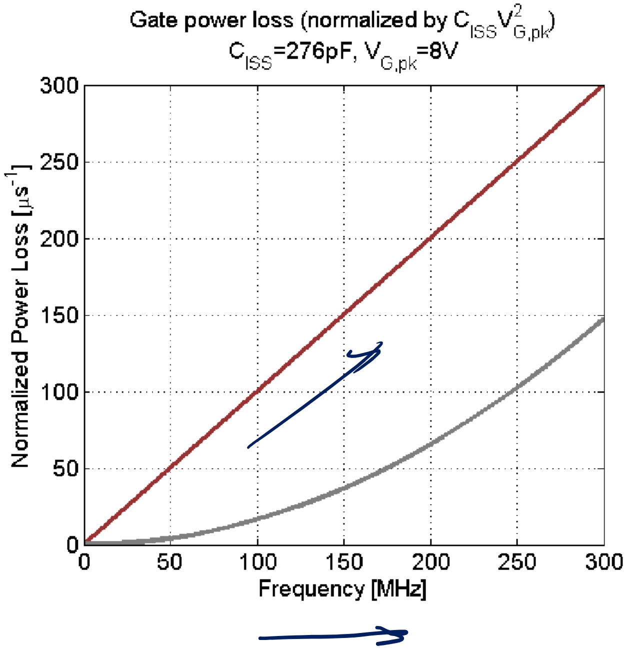
Soft Switching

- Advantages
  - Reduced switching loss
  - Possible operation at higher switching frequency
  - Lower EMI
- Disadvantages
  - Increased current and/or voltage stresses due to circulating current
  - Higher peak and rms current values
  - Complexity of analysis and modeling

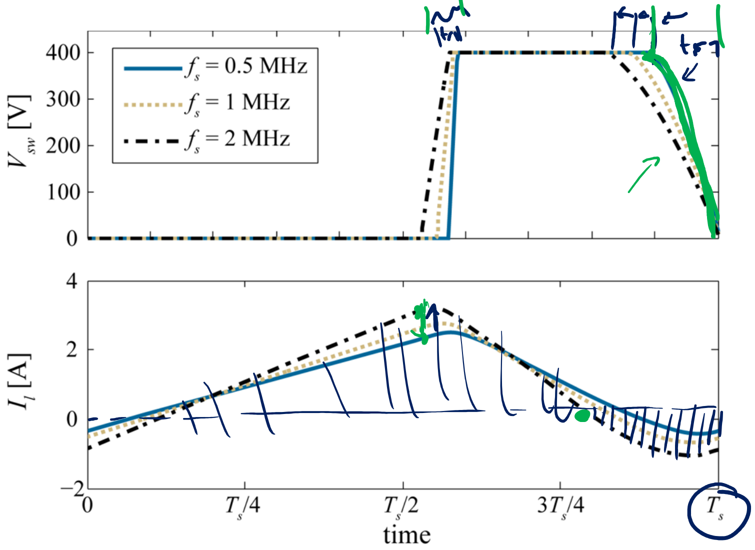
Limitations: Gate Drive

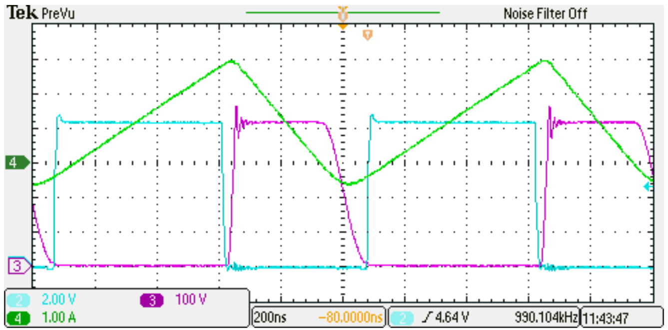
Preceeding motivation assumes vgs still square wave





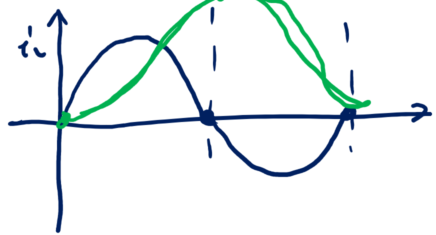
Limitations: t_d/T_s



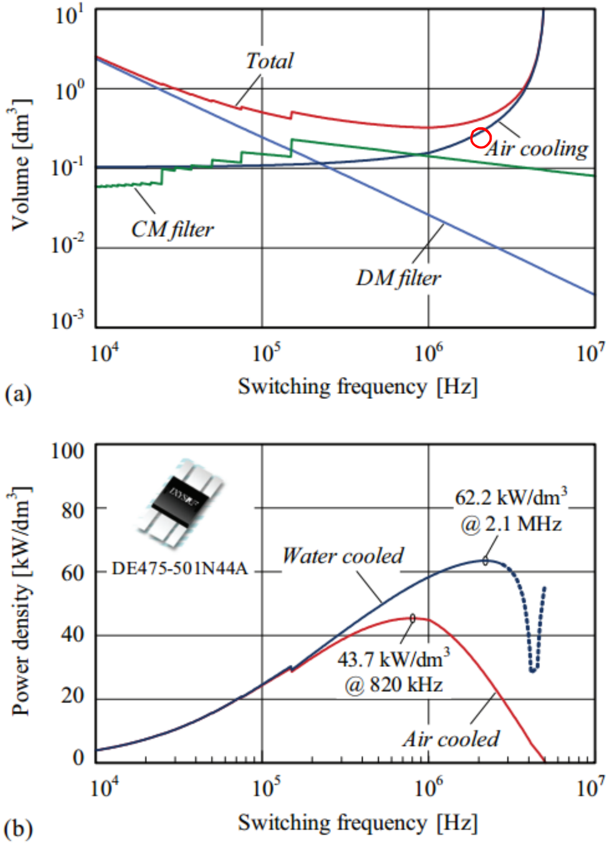


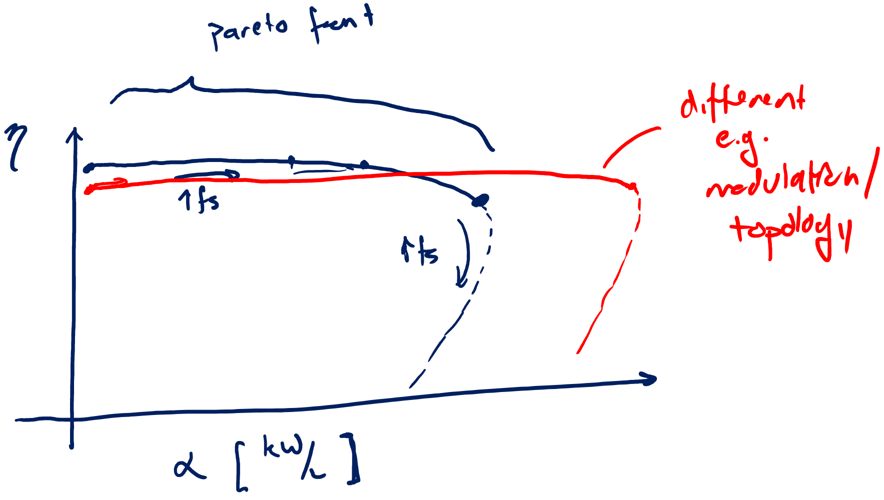
← Normalized

at the limit



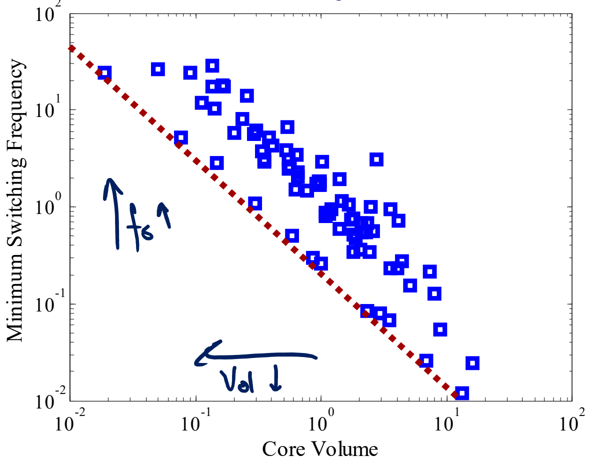
Limitations: Thermal

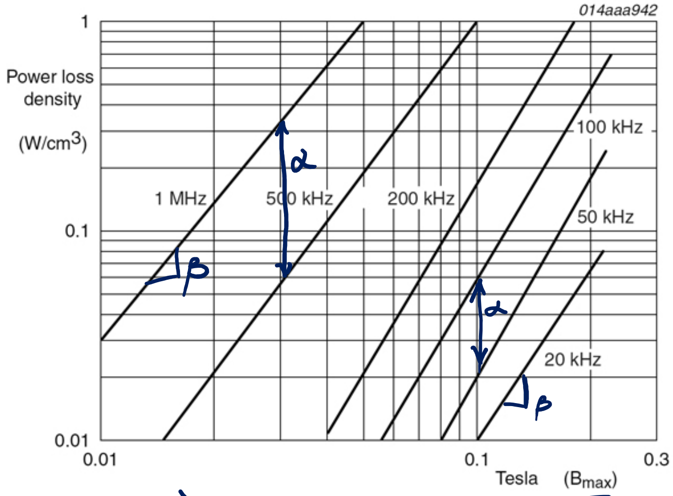




Limitations: Magnetics Design

Dual Active Bridge XF design



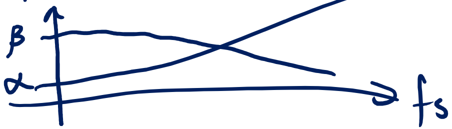


At HF ac loss mechanisms (skin, proximity, fringe, core) get worse

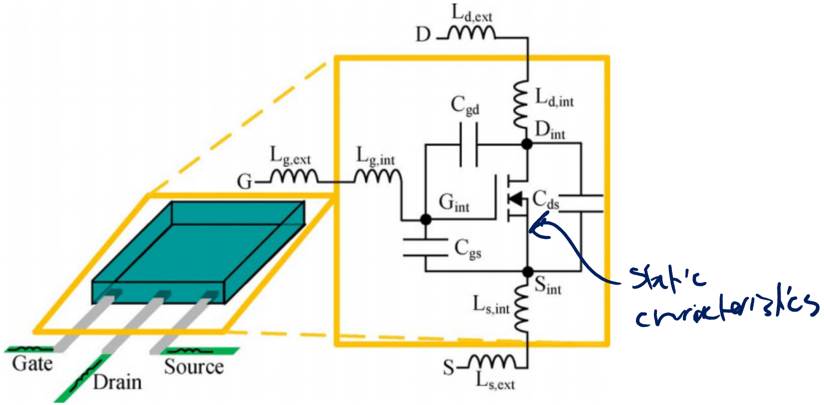
core loss $\frac{P_{core}}{V_{core}} = k_{fe} (\Delta B)^{\beta} (f_s)^{\alpha}$

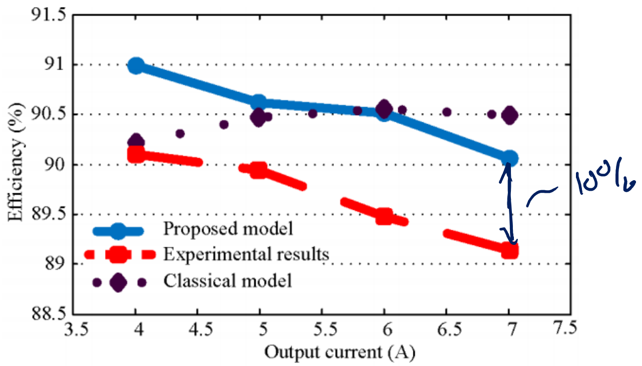
$\frac{1}{2}\Delta B$ $2 f_s$

β, α vary w/ frequency



Limitations: Circuit Modeling





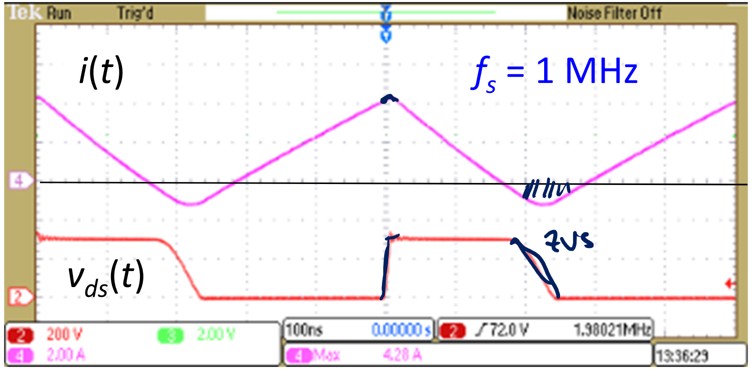
Rodríguez, M.; Rodríguez, A; Miaja, P.F.; Lamar, D.G.; Zúniga, J.S., "An Insight into the Switching Process of Power MOSFETs: An Improved Analytical Losses Model," *Power Electronics, IEEE Transactions on* , vol.25, no.6, pp.1626,1640, June 2010

150-to-400V, 150W Boost

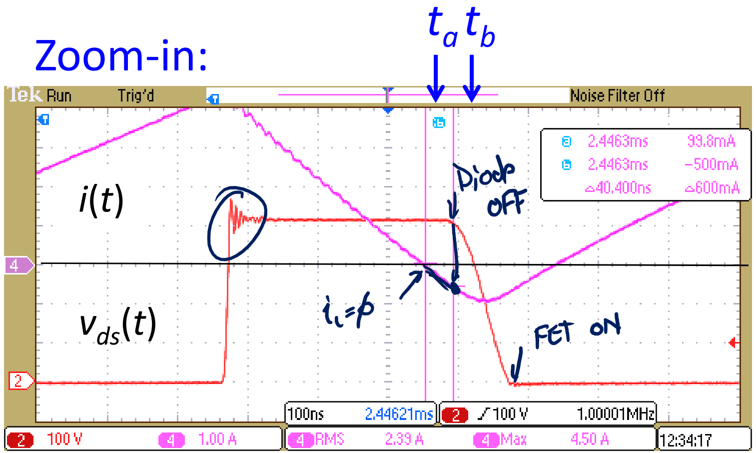
EXPERIMENTAL EXAMPLE

ZVS with Si diode

150-to-400V 150W Boost



Zoom-in:

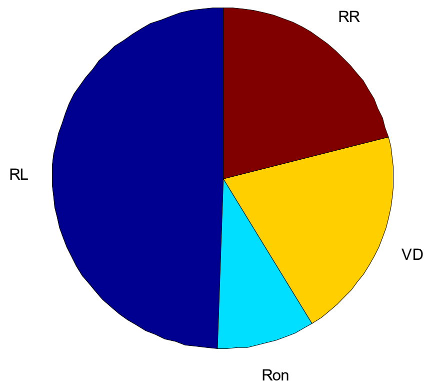


- ZVS turn-ON
  - Eliminated losses due to C_{sw} discharge during turn-ON transient
  - Eliminated losses due to MOSFET di_F/dt during turn-ON transient
- Diode reverse recovery still impacts the waveforms and losses
- Increased current ripple
  - Increased conduction losses (by >30%)
  - Increased dv_{ds}/dt upon turn-OFF, MOSFET turn-OFF speed is more important

D. Costinett, D. Maksimovic, R. Zane, A. Rodríguez and A. Vázquez, "Comparison of reverse recovery behavior of silicon and wide bandgap diodes in high frequency power converters"

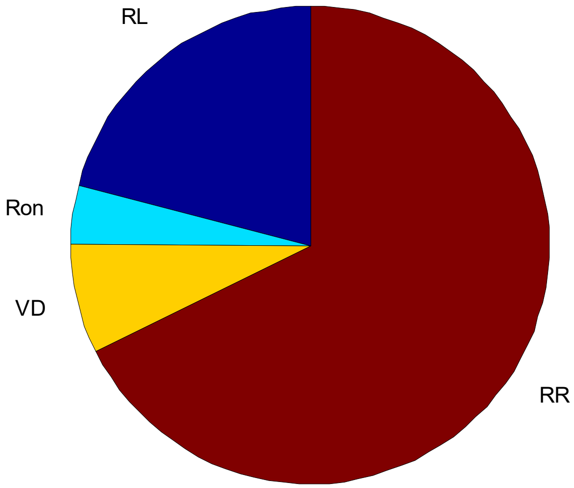
Loss Breakdown: Soft-Switched Si Boost

f_s = 100 kHz
P_{loss} = 5.7 W, η = 98.1%



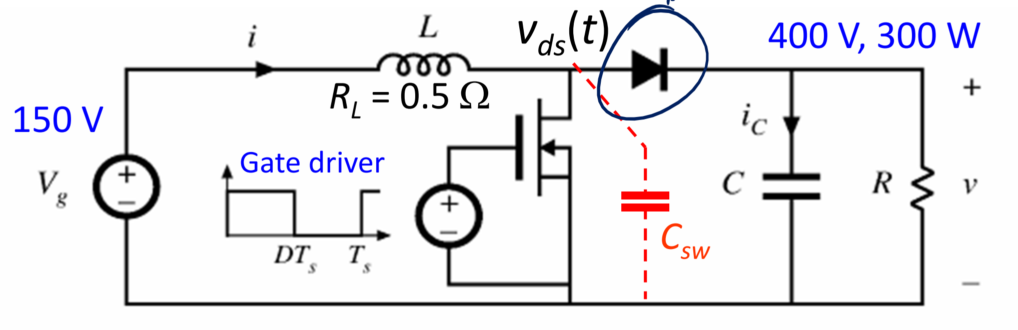
Reverse-recovery:
21% of the total loss

f_s = 1 MHz
P_{loss} = 17.7 W, η = 94.4 %
Experiment: η = 95.1 %

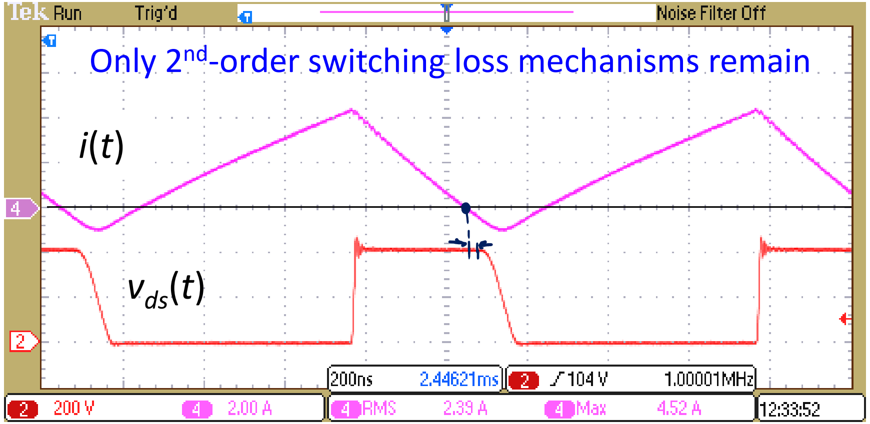


Reverse-recovery:
68% of the total loss

Soft-switched SiC diode



SiC diode, "soft-switched" operation



f_s = 1 MHz

MOSFET

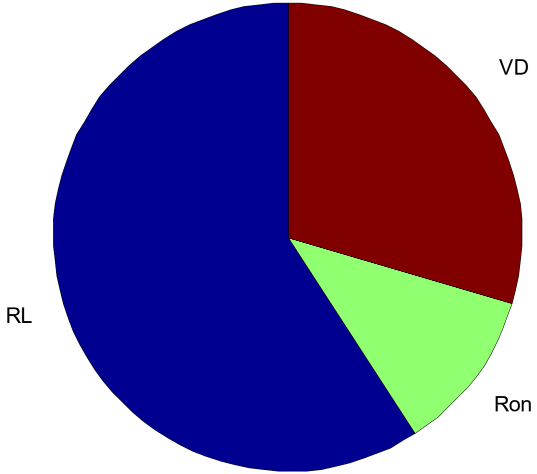
- di_F/dt = 200 A/μs
- $C_{ds,eq}$ = 45 pF
- R_{on} = 0.15 Ω

SiC diode

- $t_{rr} = 0$, $Q_{rr} = 0$
- $2C_{d,Qeq}$-$C_{d,eq}$ = 64 pF
- V_D = 1.8 V

Soft-switched Boost with SiC diode

Conduction losses only, 2nd-order switching losses not included in the model



100 kHz or 1 MHz
98.5% efficiency
P_{loss} = 4.5 W

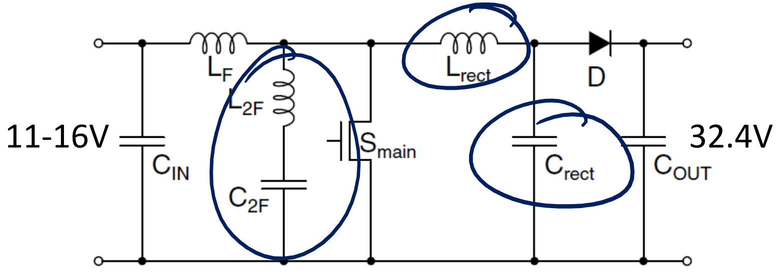
Experiments:
98.7% at 1 MHz
98.0% at 2 MHz

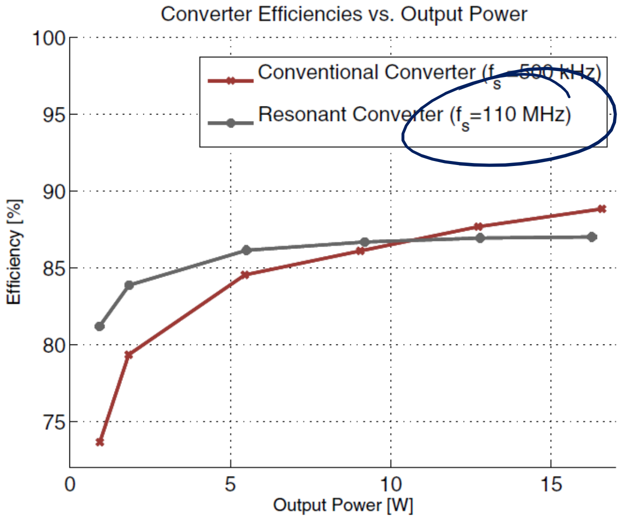
Power supply technology limits become dominated by:

- Magnetics
- 2nd-order switching loss mechanisms, e.g. gate-drive losses, parasitic inductances (layout and packaging)
- Gate-drive circuitry and controllers to support high-frequency operation

VHF power electronics [11]

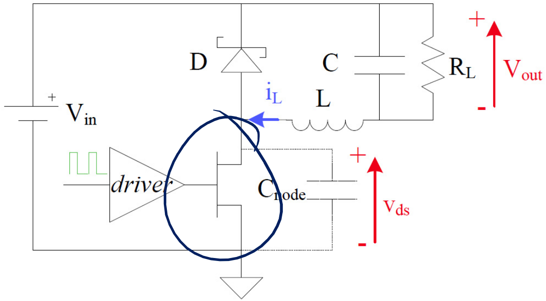
Component	Value	Type
Resonant Design		
Component	**Value**	**Type**
L_F	33 nH	Coilcraft 1812SMS
L_{2F}	12.5 nH	Coilcraft A04TG
L_{rect}	22 nH	1812SMS
C_{2F}	39 pF	ATC100A
C_{rect}	10 pF	ATC100A
C_{out}	75 μF	Multilayer Ceramics
C_{in}	22 μF	Multilayer Ceramics
S_{main}		Freescale MRF6S9060
D		Fairchild S310
Conventional Design		
Component	**Value**	**Type**
L_{boost}	10 μH	Coilcraft D03316T-103ML
C_{out}	75 μF	Multilayer Ceramics
C_{in}	22 μF	Multilayer Ceramics
S_{main}		LT1371HV
D		Fairchild S310





[11] D.J. Perreault, et..al. "Opportunities and challenges in very high frequency power conversion," IEEE APEC 2009.

WBG Devices



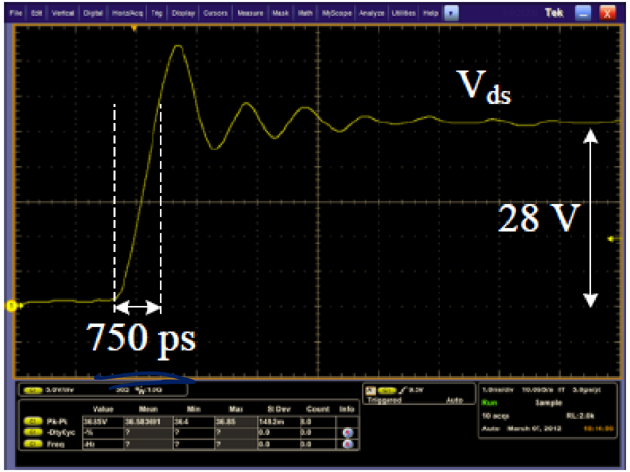
TriQuint TGF2023-02
12W, DC-to-18 GHz
RF/microwave HEMT

FOM for switching applications

$C_{ds}R_{on} \approx 1\ \Omega\text{pF}$

$Q_gR_{on} \approx 10\ \Omega\text{pC}$

Standard hard-switched PWM operation at 50 MHz
dv_{ds}/dt dominated by probe (4 pF) capacitance



Emerging GaN HEMT devices may enable completely new RF-based design approaches in power electronics

M. Rodríguez, G. Stahl, D. Costinett and D. Maksimović, "Simulation and characterization of GaN HEMT in high-frequency switched-mode power converters,"

Topics Covered

- High Frequency Power Conversion
  - Switching losses and device selection
  - Nonlinear device capacitances
  - Resonance in power electronics
  - Soft switching (ZVS and ZCS)
- Resonant Converters
  - State-plane analysis
  - Resonant converter topologies
  - Sinusoidal analysis
  - AC-modeling and frequency modulation
- Non-resonant soft switching converters
  - State-plane analysis
  - Constant frequency control
  - Resonant switches
  - Modeling and Simulation
  - Discrete time models
- Switched capacitor converters
  - SSL and FSL operation
  - Charge vector modeling
  - Soft-charging operation
- Applications and practical issues of high frequency converters