Massachusetts Institute of Technology

Laboratory for Electromagnetic and Electronic Systems

Design of Miniaturized, Isolated dc-dc Converters Operating at Radio Frequencies

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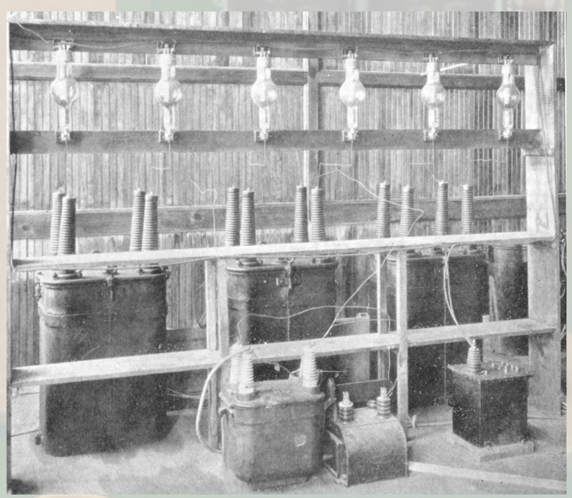
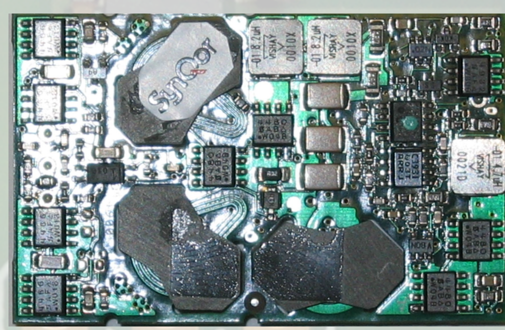
PowerSoC 2012

November 17, 2012



20 kW Kenotron Rectifier, Circa 1926
(From Principles of Rectifier Circuits, Prince and Vogdes, McGraw Hill 1927)



Server Power Supply, Circa 2006
(Manufactured by Synqor)

??

Circa 2016

FINSix

Isolated, Integrated VHF Power Converters

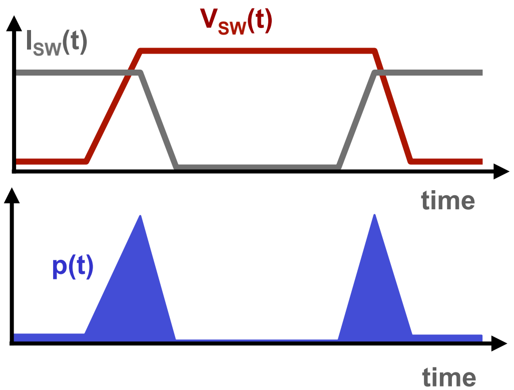
- The main objective of this research is to develop technologies for miniaturized, integrated power converters operating at VHF (30 – 300 MHz)
  - Miniaturization
  - Integration
  - Performance (Bandwidth,…)

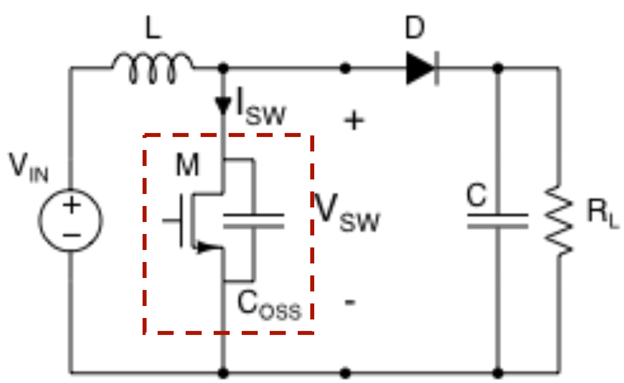
- This talk describes:
  1. A topology and associated controls for isolated power converters at VHF, 10’s of V & W demonstrated at 75 MHz
  2. Synthesis and optimization of coreless planar printed-circuit board transformers for this topology
  3. IC integration of power devices and resonant gate drive to yield a miniaturized, integrated power converter
  4. Opportunities and challenges for the future

Switching Frequency Limitations

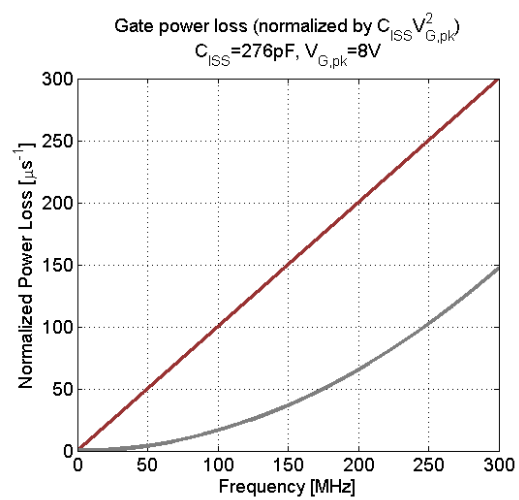
- **Loss mechanisms in power electronics limit switching frequencies**
  - **Relative importance of different losses depends on power, voltage**

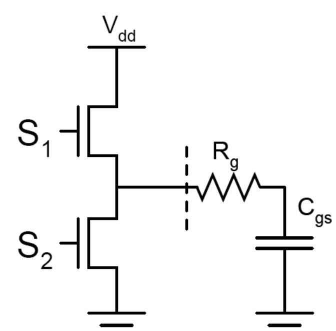
- **Switching loss ($\propto f$)**



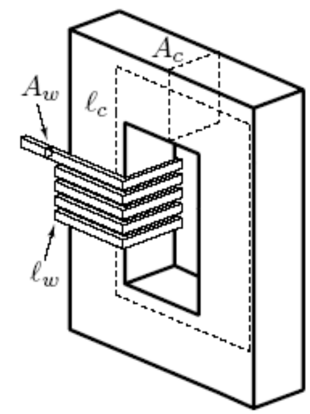


- **Gating loss ($\propto f$)**





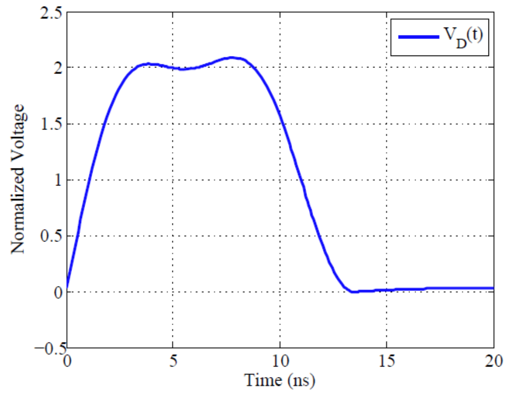
- **Core loss in magnetic materials ($\propto f^k$)**

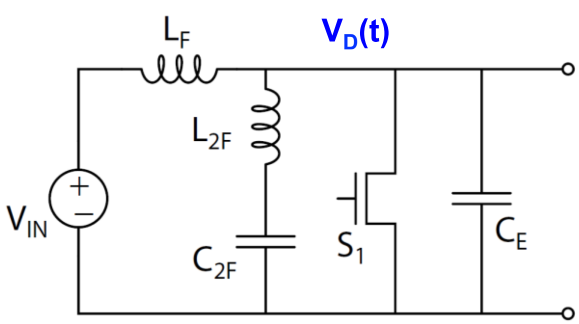


Switching Frequency Solutions

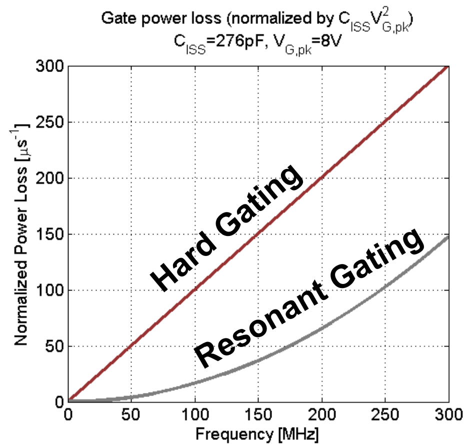
- Minimize frequency dependent device loss, switch fast enough to change or eliminate magnetic materials

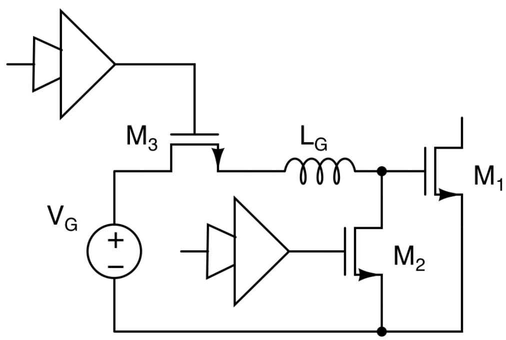
- ZVS Soft switching



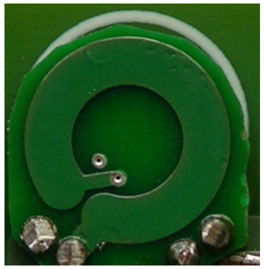


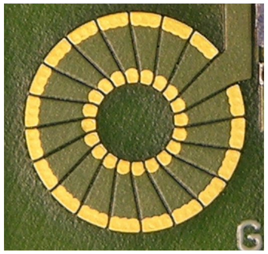
- Resonant gating



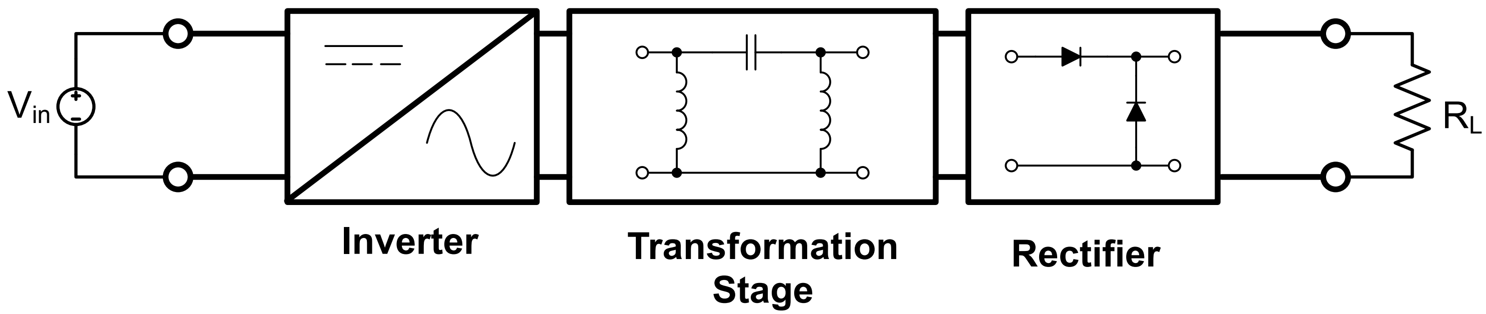


- Coreless magnetics in package or substrate





Desired Cell Topology Characteristics



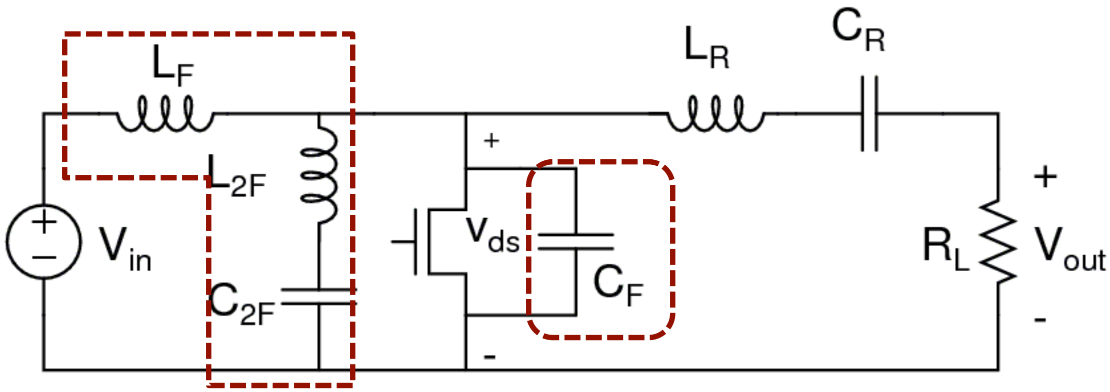
- **Subsystems: Inverter, transformation/isolation, rectifier, controls**

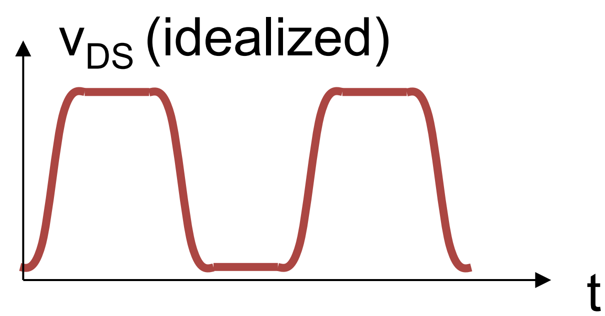
- **Efficient operation at VHF (> 30 MHz)**
  - **ZVS switching, resonant gating**
  - **Topology *must* absorb device and interconnect parasitics**
  - **Switch control ports referenced to fixed potentials (for mid-to-high V)**

- **Low component count and device voltage & current stress**
  - **Facilitate isolation and integration of passive components**

- **Compatible with resonant gating and On/Off control**
  - **Avoid bulk magnetic storage in power stage**
  - **Fixed/narrow frequency, duty ratio preferred**

Inverter Topology: Φ2 Inverter



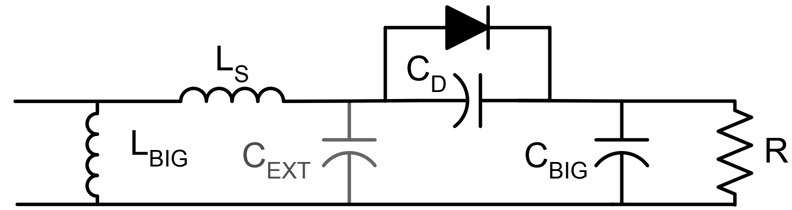


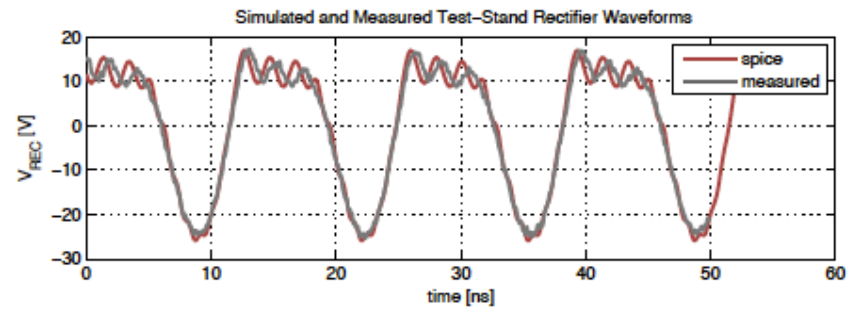
- **Multi-resonant network shapes the switch voltage to a quasi-square wave**
  - **Network nulls the second harmonic and presents high impedance near the fundamental and the third harmonic**
  - **Reduces peak voltage ~ 25-40% as compared to class E**
  - **Reduces sensitivity of ZVS switching to load characteristics**
- **No bulk inductance (all inductors are resonant)**
  - **Small inductor size**
  - **Fast transient performance for on-off control**
- **Absorbs device capacitance in a flexible manner**

Rivas, et. al., "A High-Frequency Resonant Inverter Topology with Low Voltage Stress," Trans. P.E., July 2008

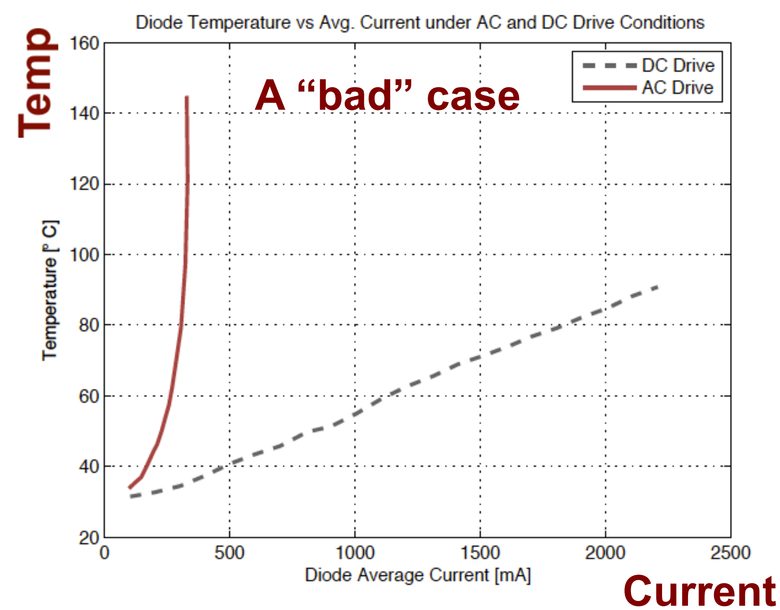
Series-Loaded Resonant Rectifier

- Absorbs diode capacitance as part of operation
  - If no external C used, can also absorb diode package L
  - Tune to provide desired impedance at fundamental



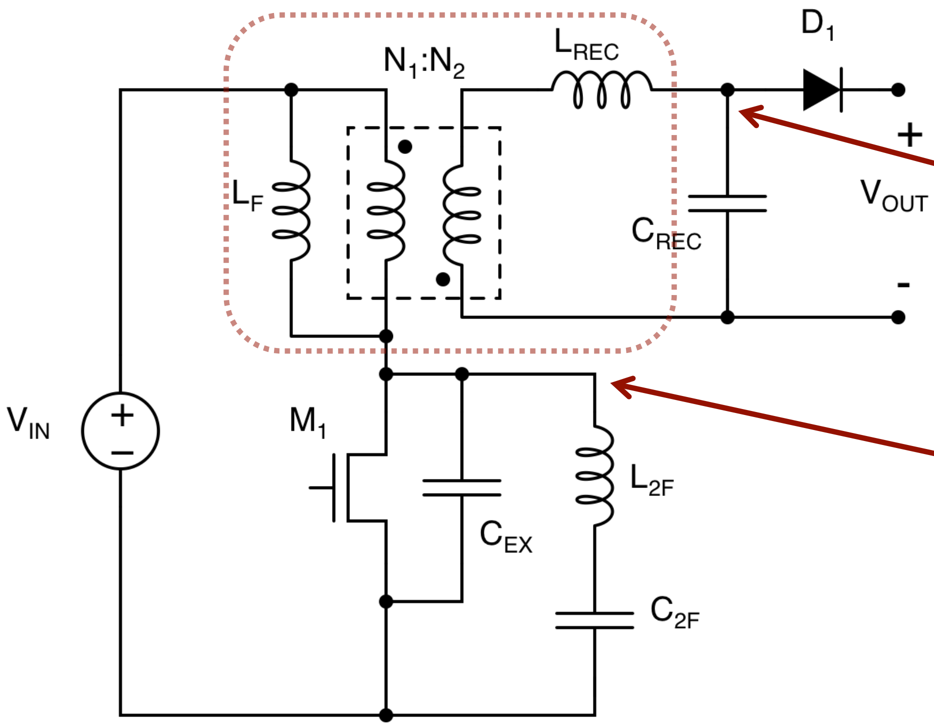


- Not all Schottky diodes work well at VHF
  - Loss at VHF can greatly exceed low-frequency loss
  - Sometimes must significantly derate diode current
- Still: efficient resonant rectification at VHF and UHF

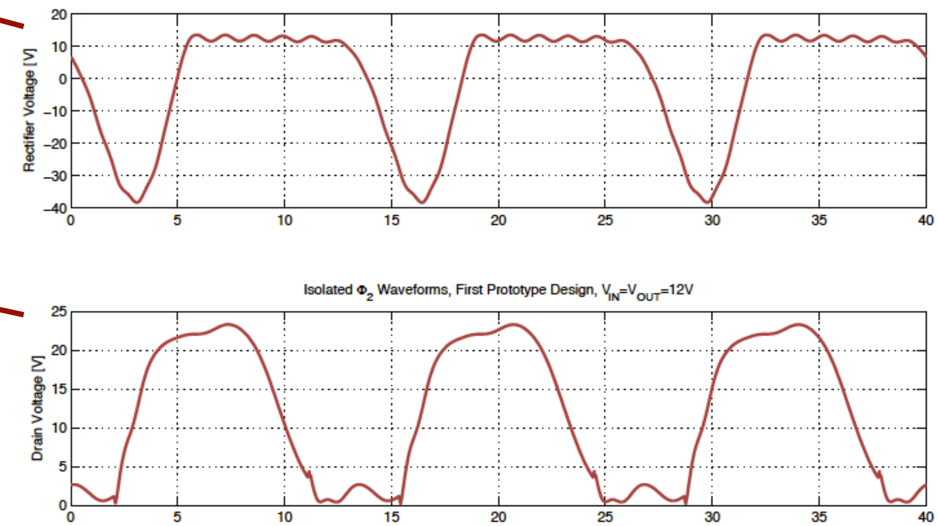


Nitz, et al., "A New Family of Resonant Rectifier Circuits for High-Frequency dc-dc Converter Applications, APEC '88

Isolated VHF dc-dc topology



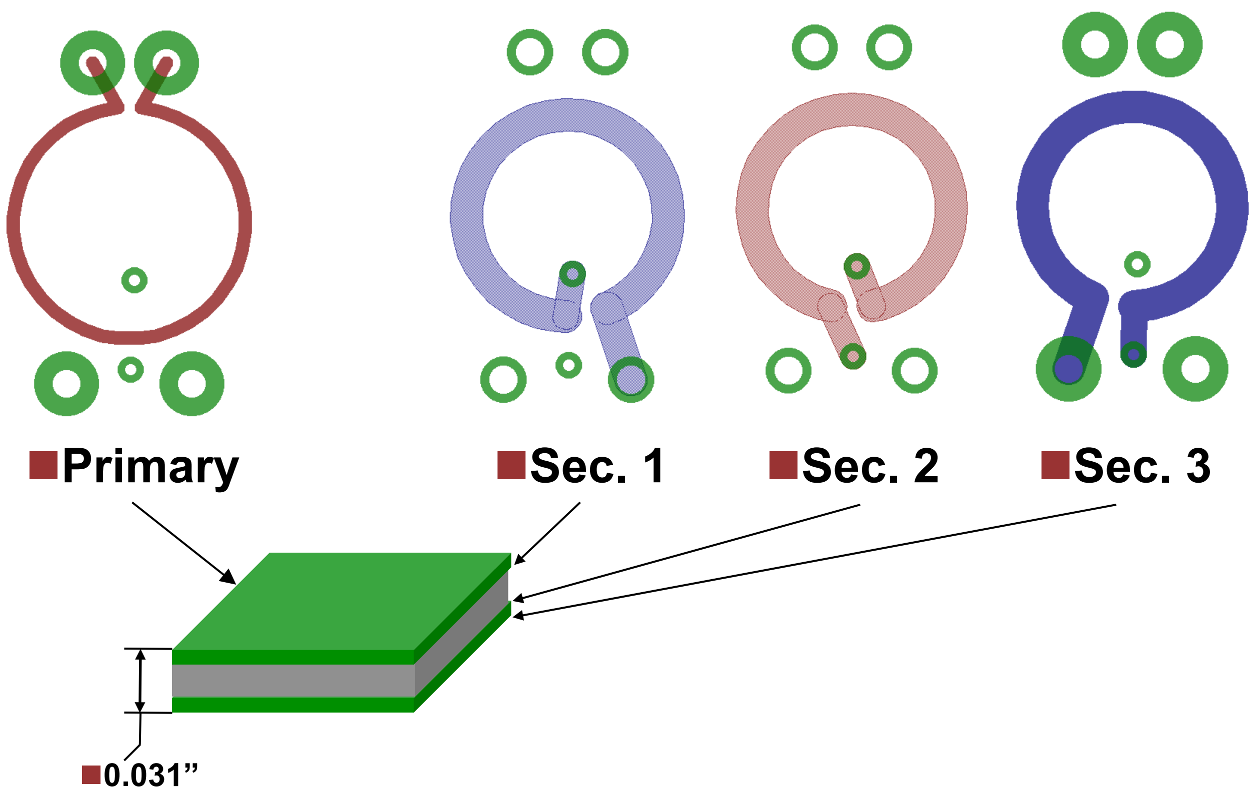
- Isolated $\Phi 2$ inverter and resonant rectifier



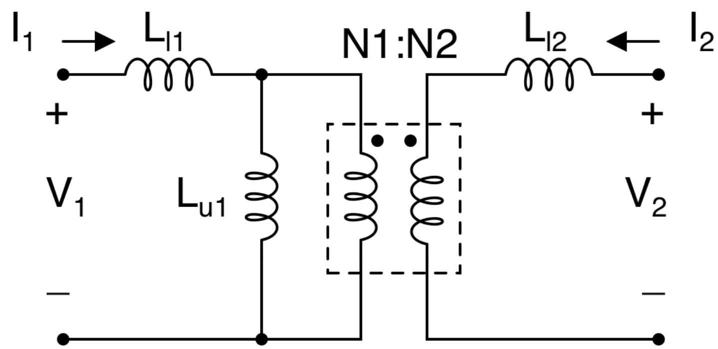
- Use the primary inductance L_{11} of a transformer as the resonant element L_f in a Φ_2 tuning network
- Use transformer leakage inductance (of the cantilever model) as the resonant inductor for a resonant rectifier
- Isolated converter with a low component count!
- Control via on/off control

Coreless Planar PCB Transformer

- Design transformer as a planar structure in a printed circuit board
- 4-layer PCB, 0.031” thickness for initial prototypes



Transformer Model



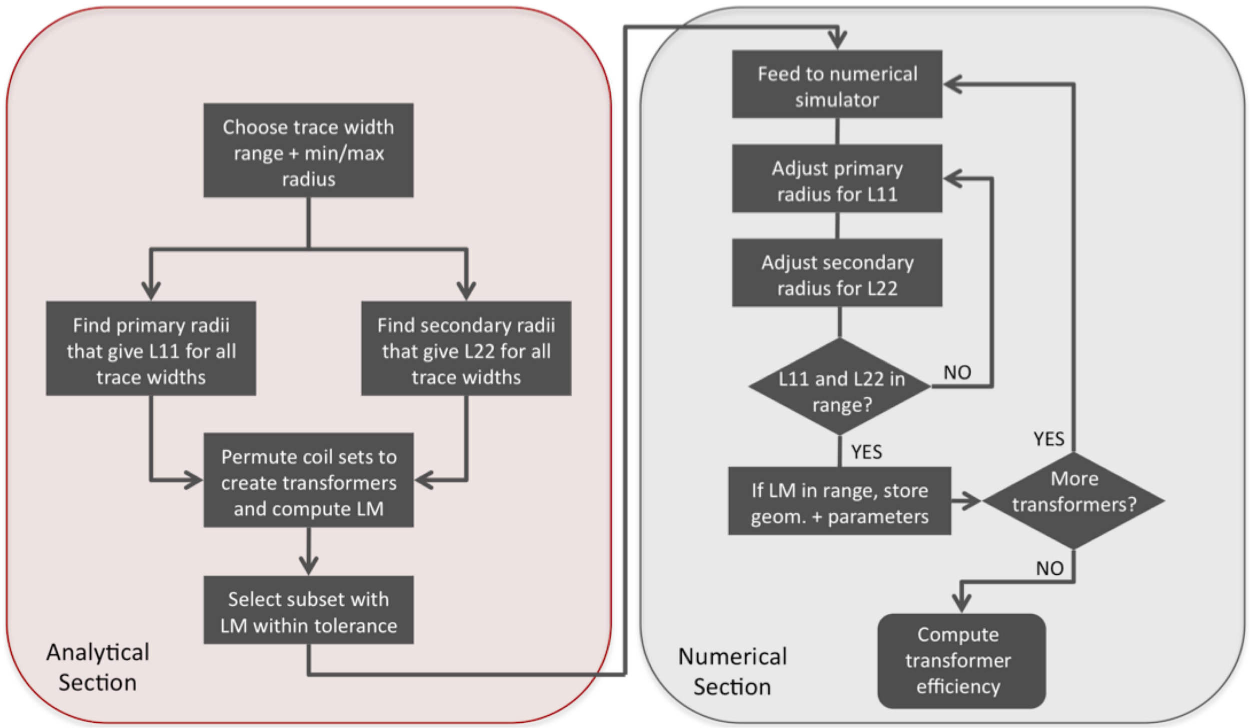
$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_M \\ L_M & L_{22} \end{bmatrix} \cdot \begin{bmatrix} i_1' \\ i_2' \end{bmatrix}$$

$$L_{11} = L_{\ell 1} + L_{\mu 1} \qquad L_{22} = L_{\ell 2} + \left(\frac{N_2}{N_1}\right)^2 \cdot L_{\mu 1}$$

$$L_M = \left(\frac{N_2}{N_1}\right) \cdot L_{\mu 1}$$

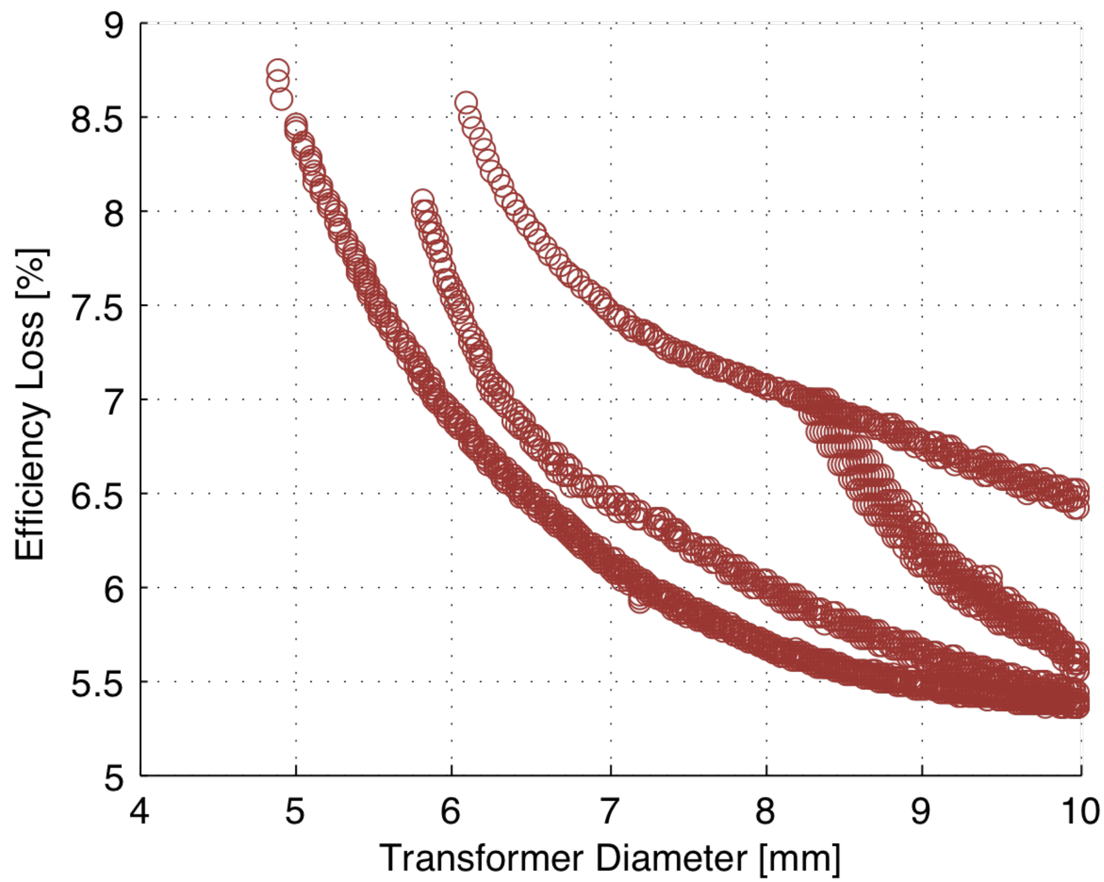
- **Once a converter is designed, the inductance matrix is constrained by the component values**
- **A given structure maps to a single inductance matrix, but a single matrix maps to many structures**
- **We want the structure that best trades size and loss**

Synthesis Algorithm



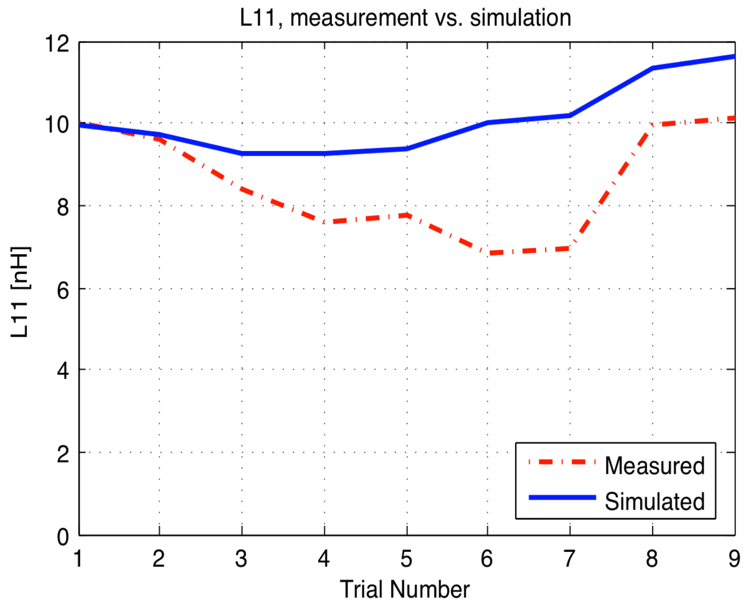
- Use analytical expressions to find geometry locus
- Numerical simulation accounts for proximity/skin effects
- Optimization search can be easily parallelized

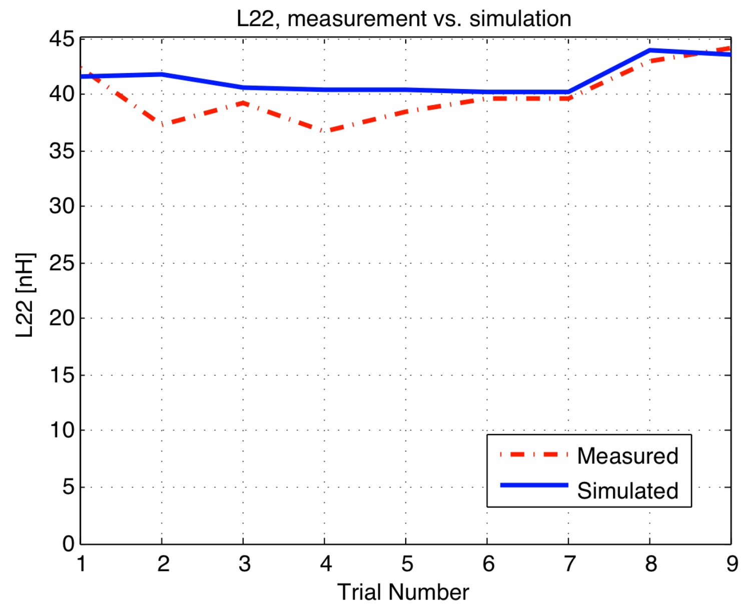
Scatter Plot of Loss vs. Diameter

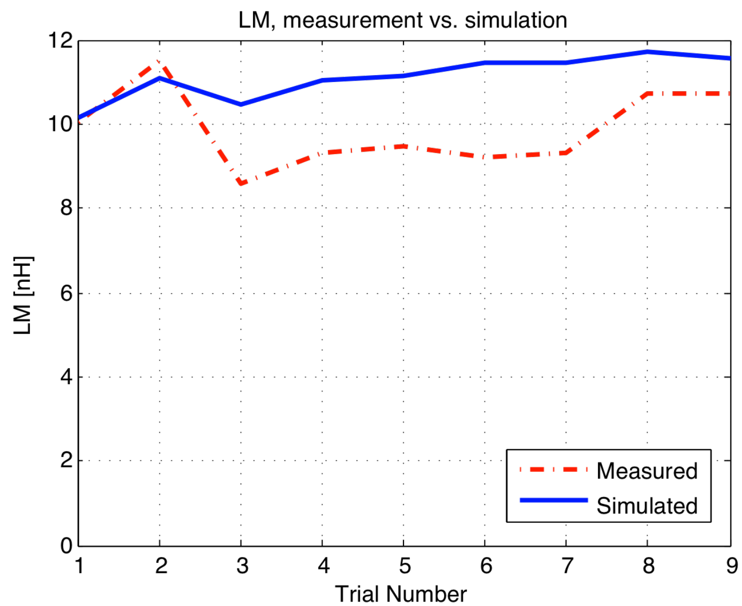


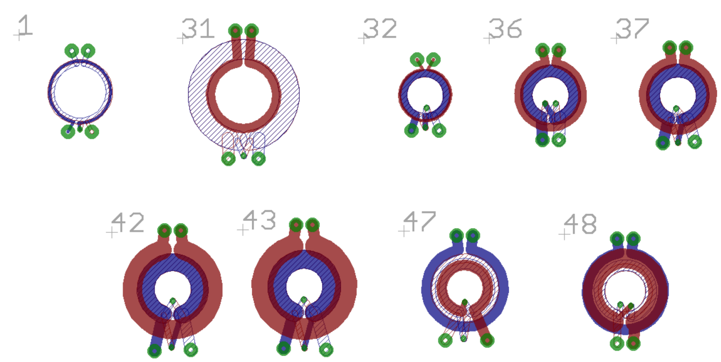
- Loss-diameter boundary easy to resolve
  - For this L-matrix, 1-turn primary, 3-turn secondary
- Selected ~8 mm diameter transformer for prototype

Inductance: Measured vs. Simulation

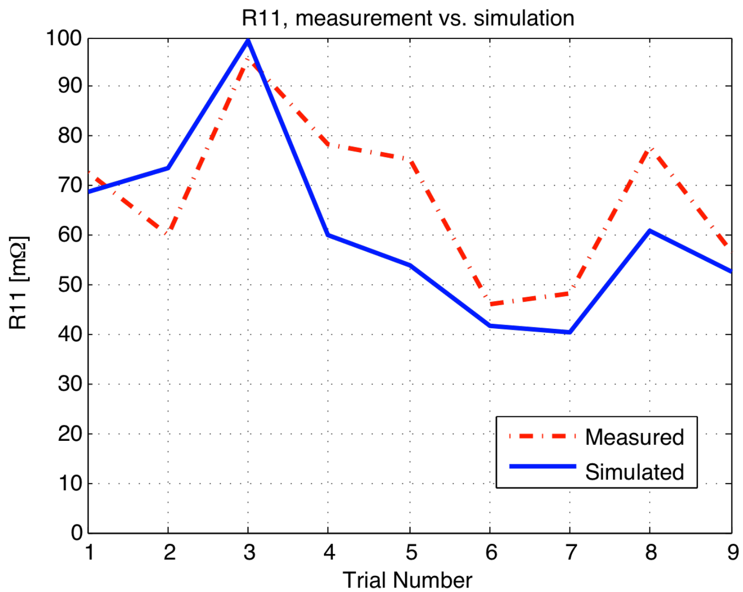


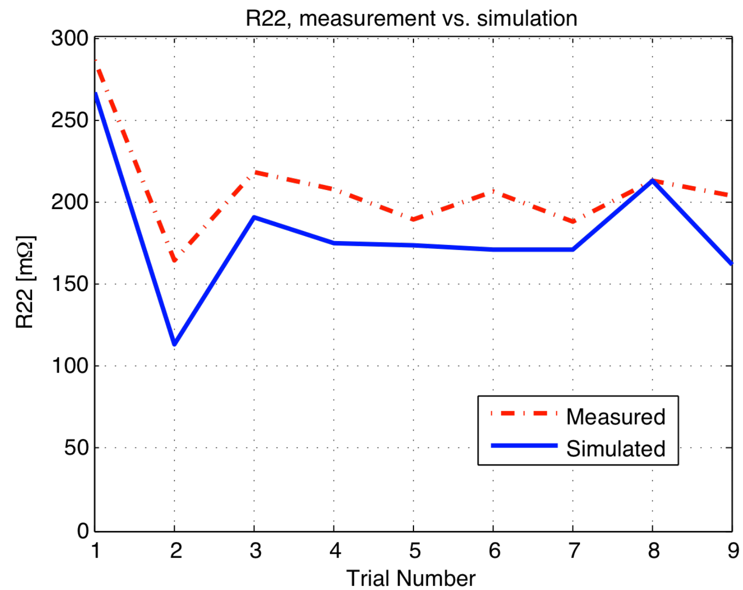


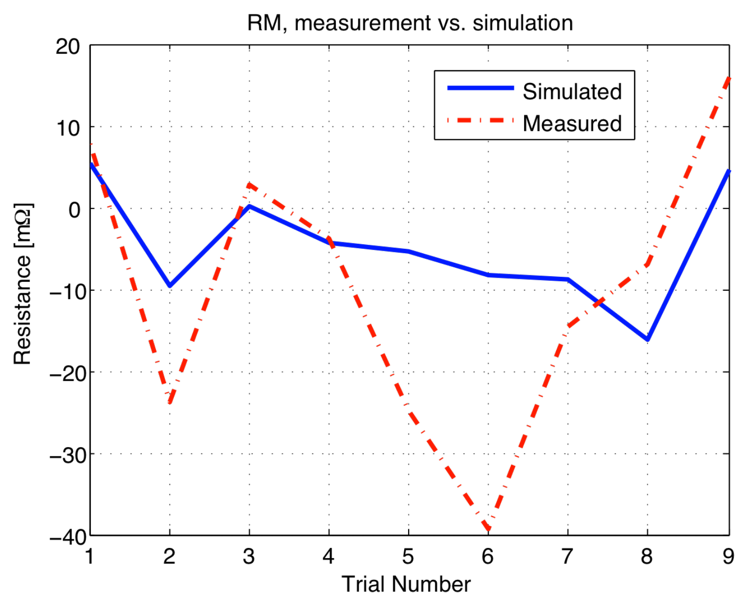




Resistance: Measured vs. Simulation

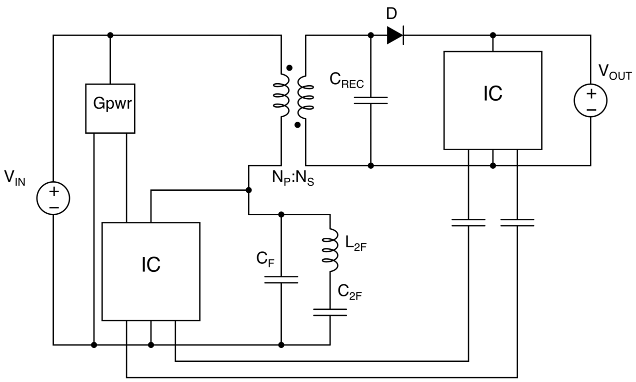




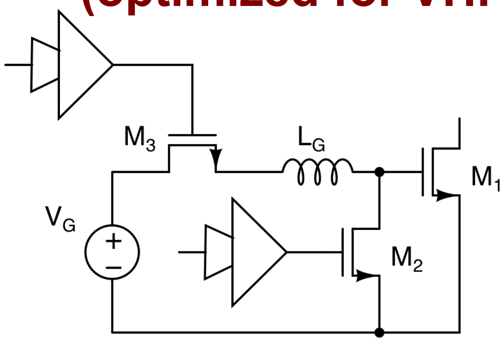


- Inductance error: ~ 2nH
- Resistance error: ~ 30mΩ
- Transformer Efficiency:
  - 85% - 93% (5 mm – 10 mm)
- Transmitted Power:
  - 9.6 W

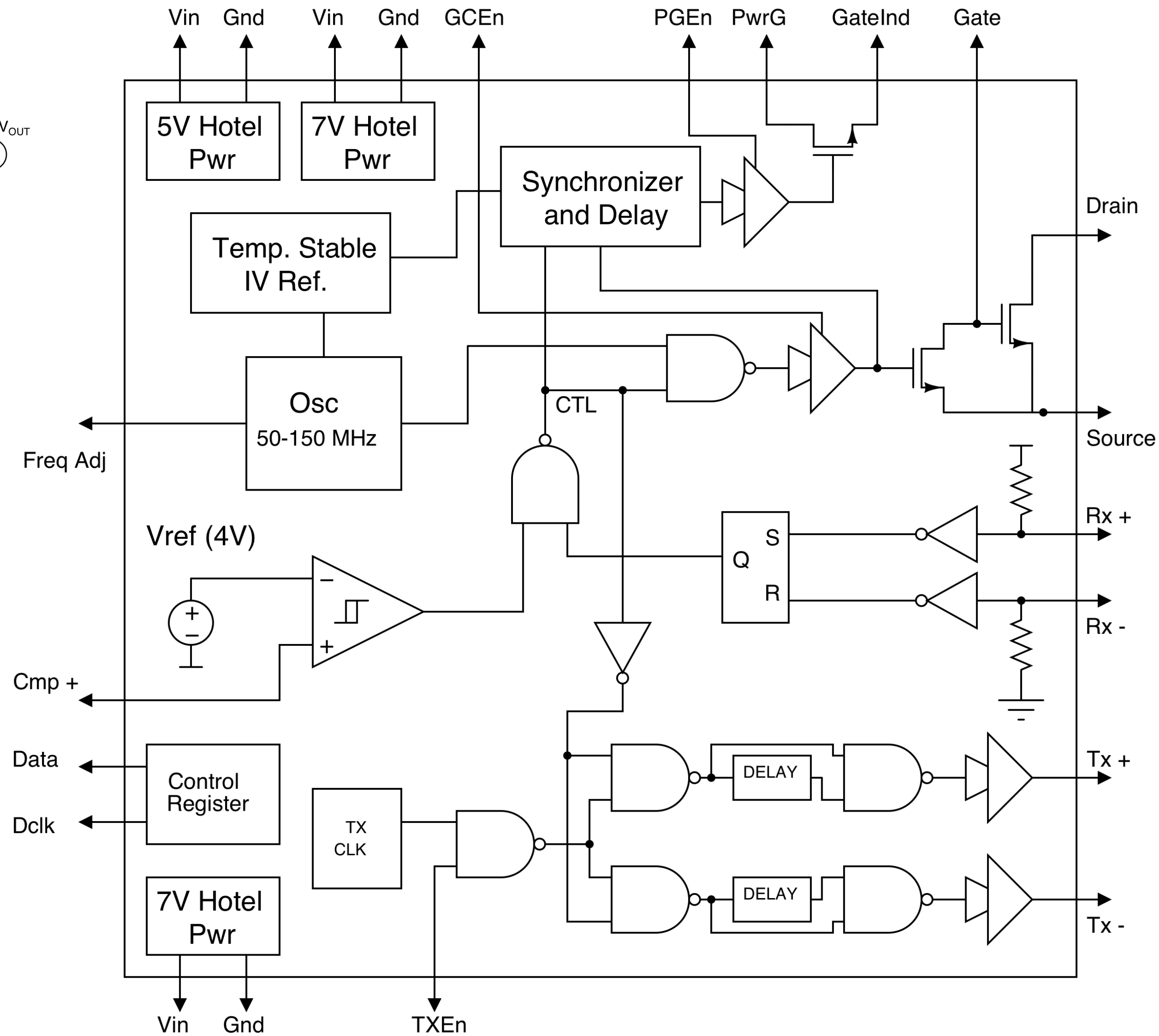
Block Diagram – Integrated VHF Converter



IC Integration of LDMOS power device (optimized for VHF)



IC integrated half-sine resonant gate drive



Integrated controls and power devices

LDMOS Device Optimization - 1

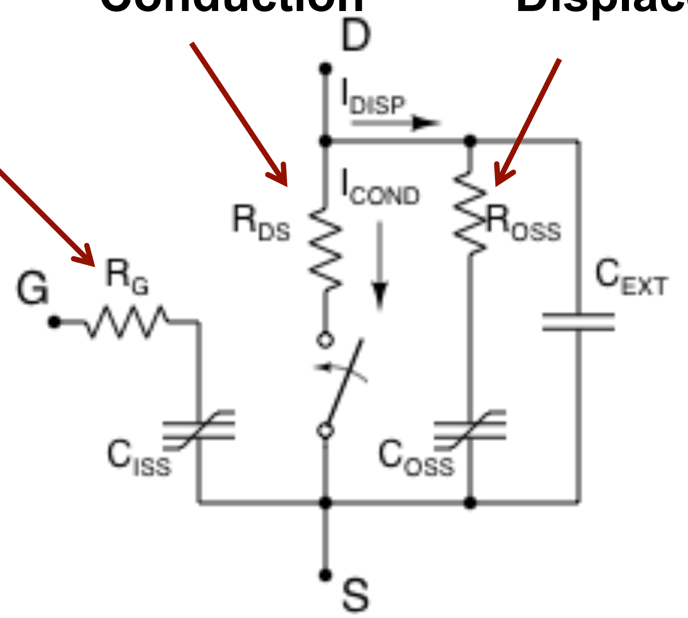
- At 10's of V, discrete Si RF LDMOS devices can operate efficiently to 200+ MHz (with ZVS, resonant drive)
- Integrated power processes for LDMOS devices are not currently optimized for VHF
- Losses, FOM are DIFFERENT for ZVS, resonant drive

$$P_{TOT} = \underbrace{K_1 \cdot R_G \cdot C_{ISS}^2}_{\text{Gating}} + \underbrace{K_2 \cdot R_{DS-ON}}_{\text{Conduction}} + \underbrace{K_3 \cdot R_{OSS} \cdot C_{OSS}^2}_{\text{Displacement}}$$

$$K_1 = 2\left(\pi \cdot V_{G,AC} \cdot f_{SW}\right)^2$$

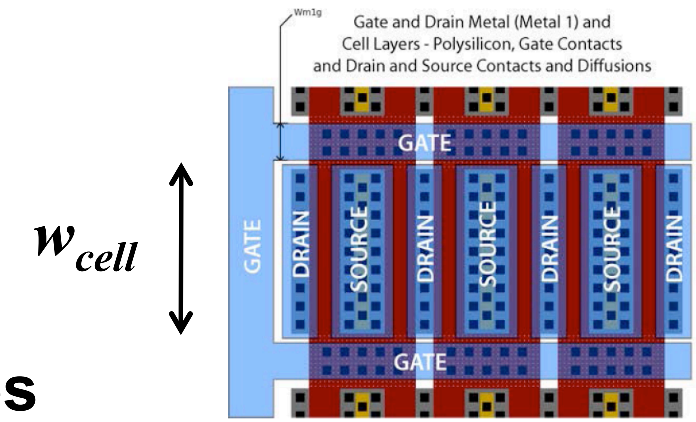
$$K_2 = I_{COND,RMS}^2$$

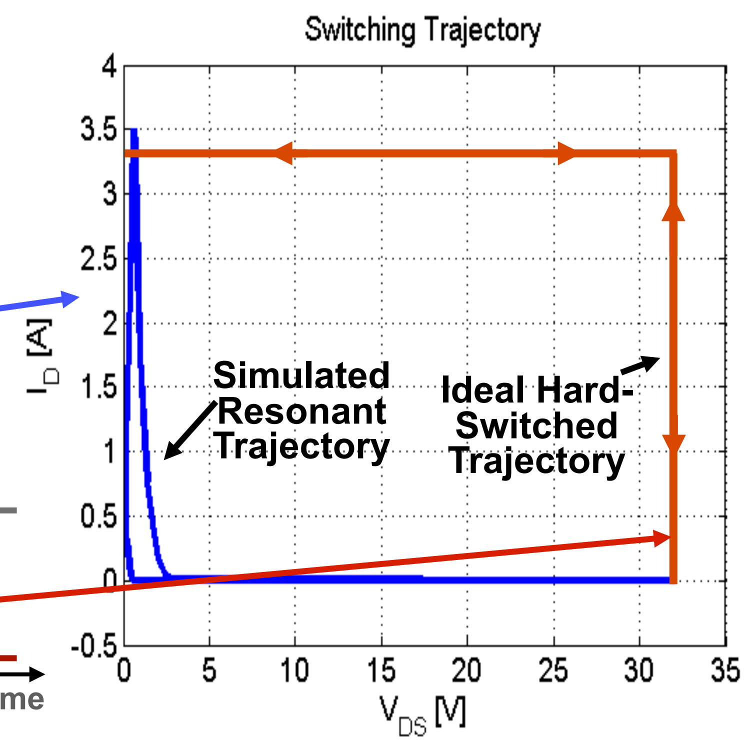
$$K_3 = \left(\frac{I_{DISP,RMS}}{C_{TOT}}\right)^2$$

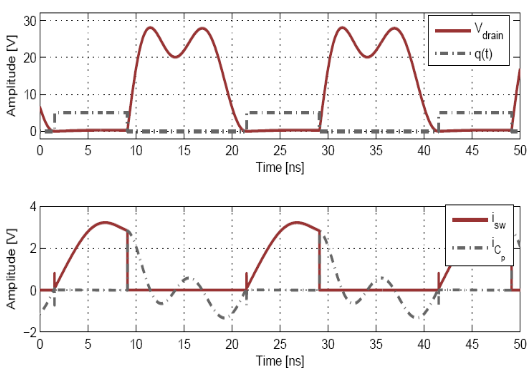


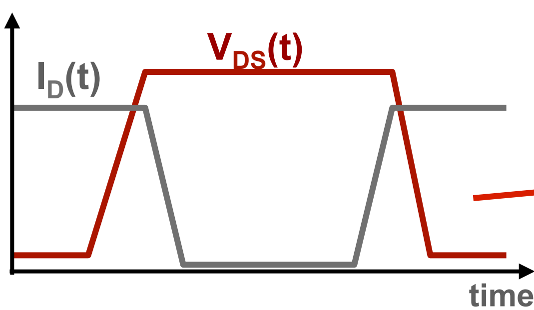
LDMOS Device Optimization - 2

- Even in current BCD processes, there is great benefit to CAD optimization of LDMOS device layout for VHF operation
- Resonant soft switching mitigates hot-carrier effects; sometimes enables “uprating” of devices
- **56% reduction in device loss demonstrated in one case!**



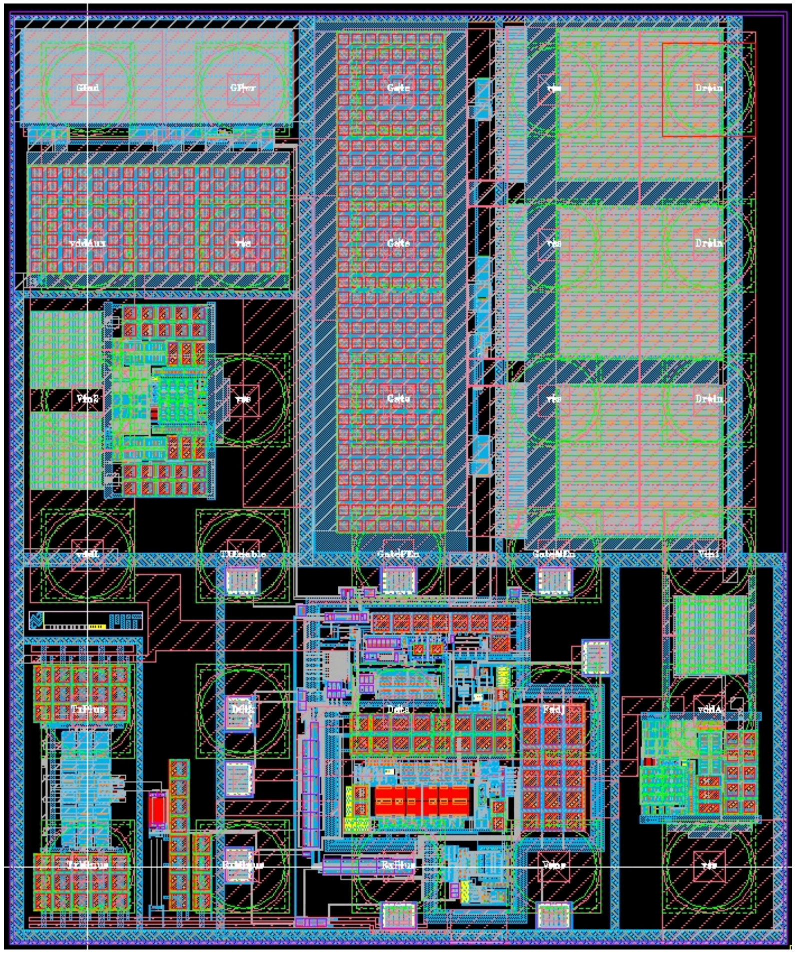






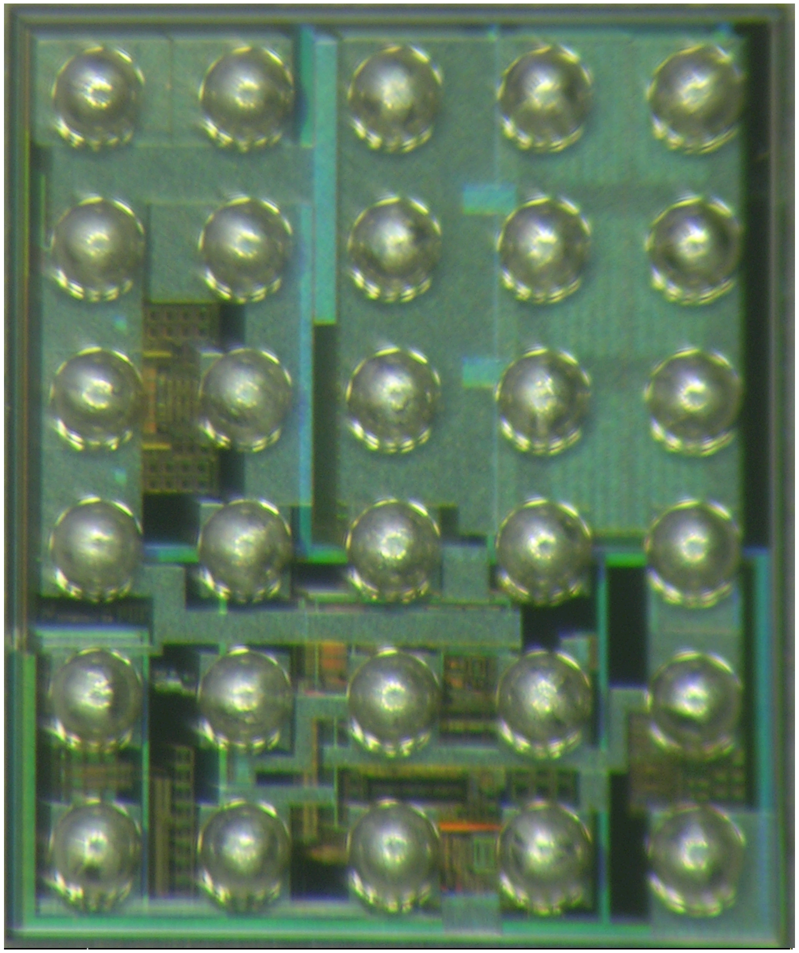
Sagneri, et. al., “Optimization of Integrated Transistors for Very High Frequency dc-dc Converters,” Trans. P.E (in press)

Converter IC Layout



- 2.5 mm x 3 mm Flip-Chip
- Power Devices
- Gate Driver, Oscillator
- Control
- Capacitive feedback across isolation
- Isolated/Non-isolated
- Hotel Supply

Converter IC Die Photo



- 2.5 mm x 3 mm Flip-Chip
- Power Devices
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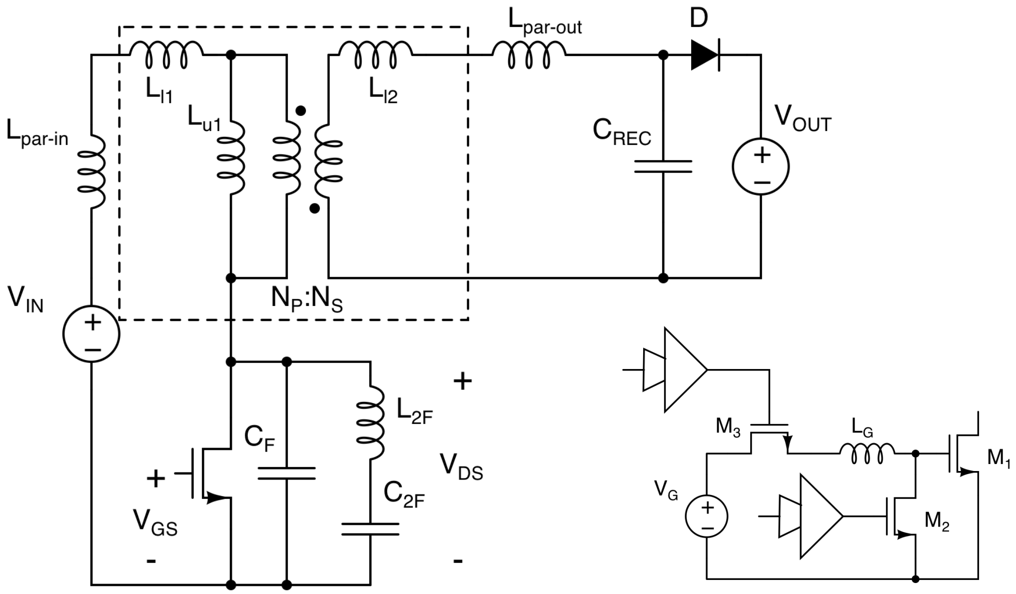
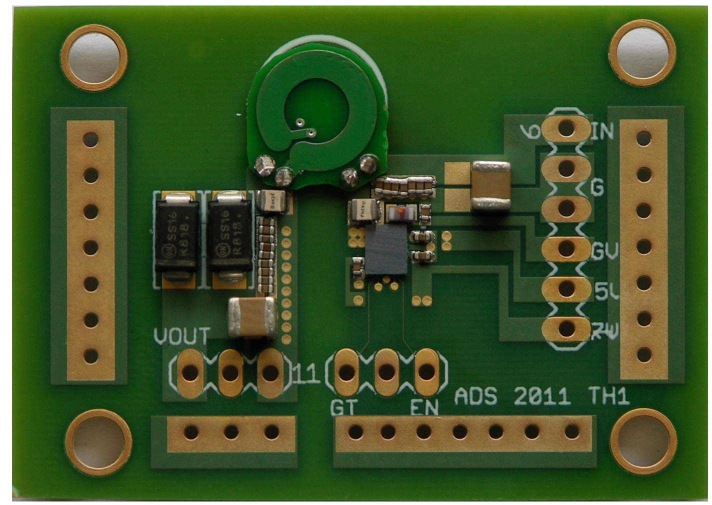
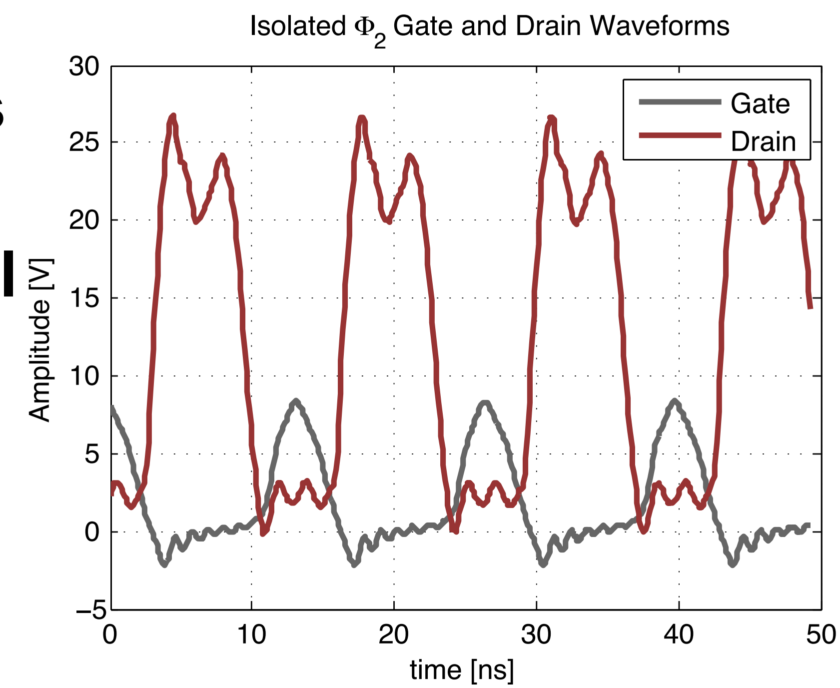
Isolated 75 MHz Φ_2 Converter Results



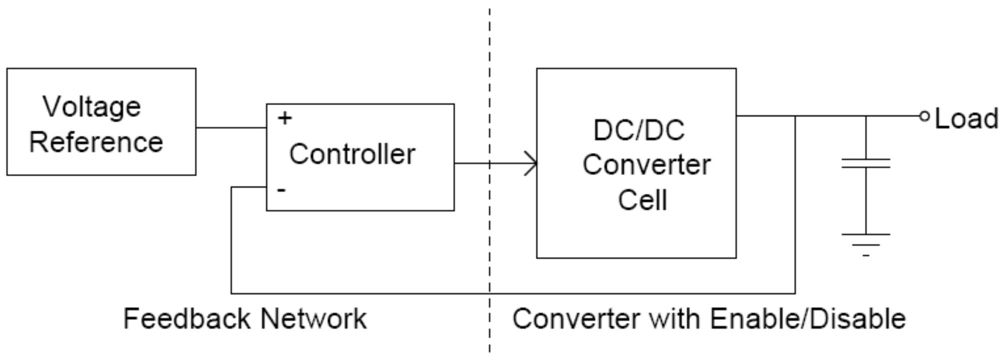


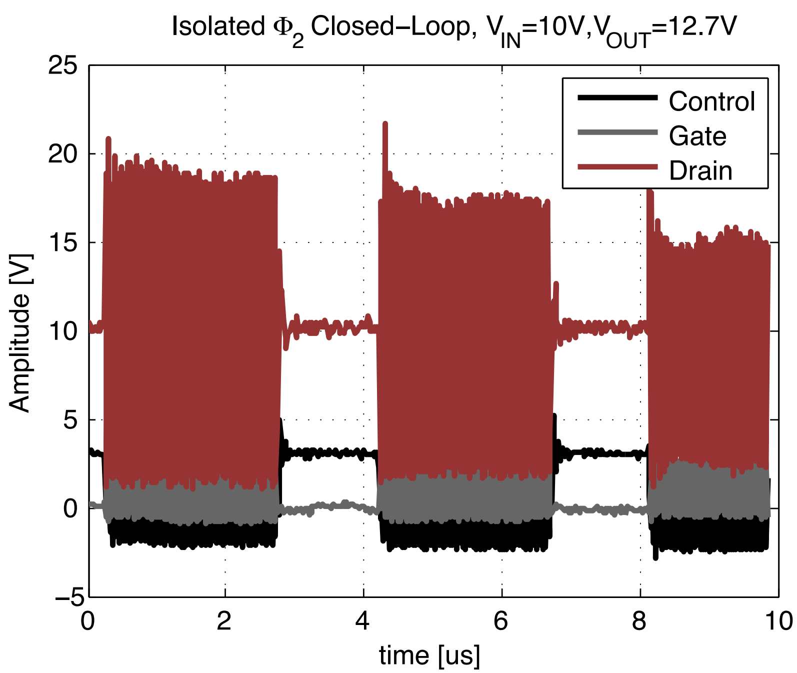


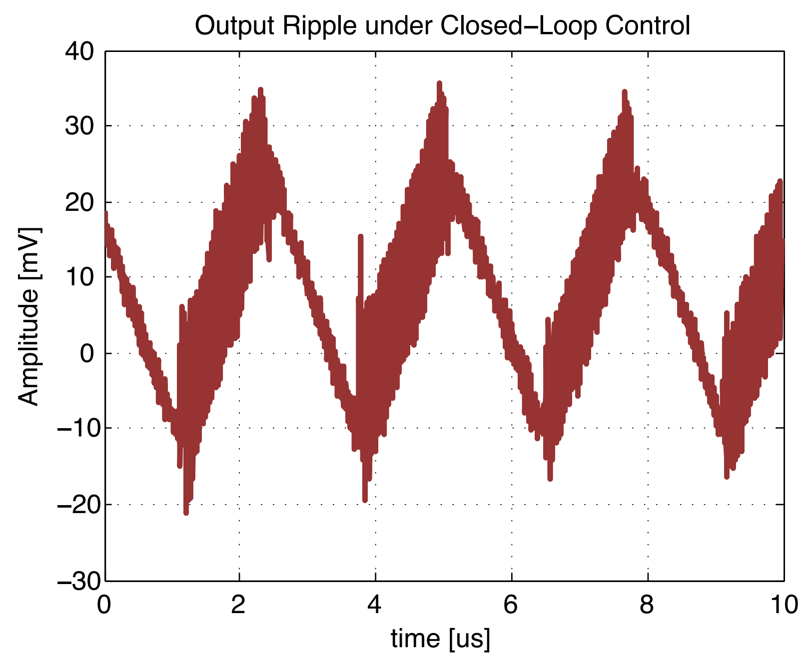
- ZVS resonant operation across operating range
- Half-sine gate driver works well
  - Pgate ~ 110 mW @ 75 MHz, ~ 3x improvement over hard gating
- Efficiency 66%-76% across voltage, load range
  - On-off control

Closed-Loop Operation – On/Off Control

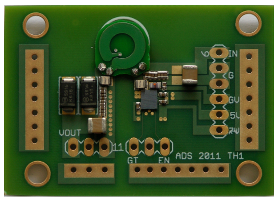
- On/Off Control to regulate output
  - Regulates to 12.7 V with 0.4% ripple

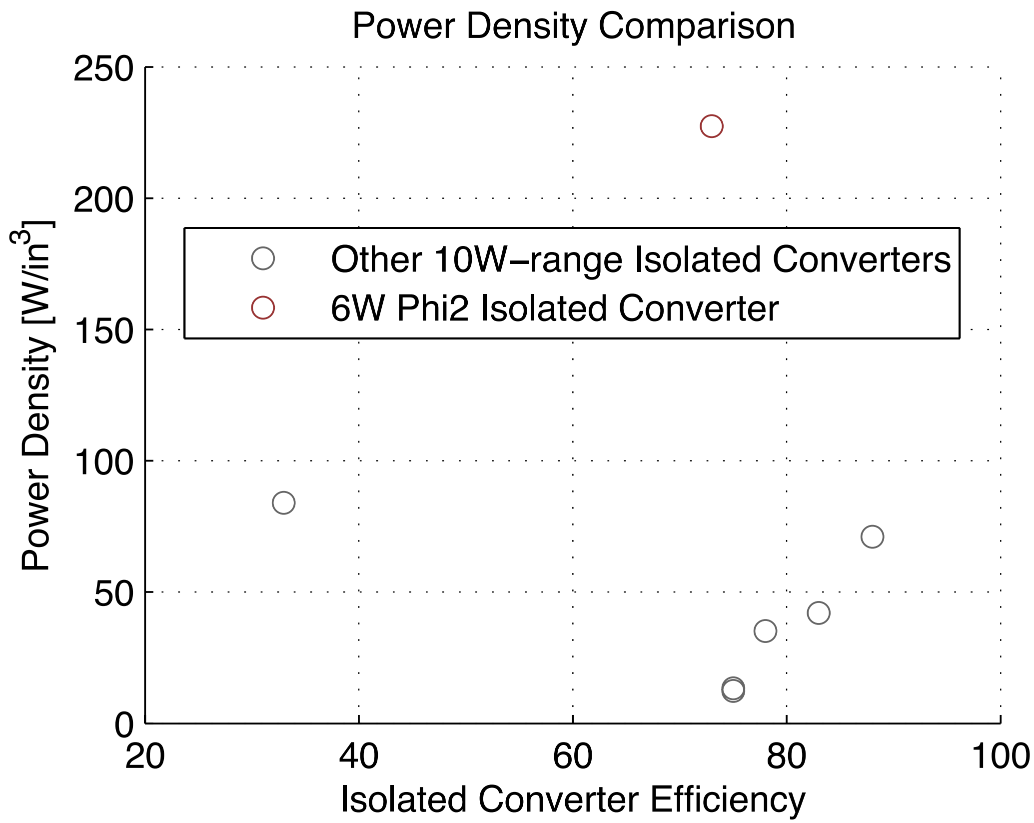






Power Density, Efficiency, Integration

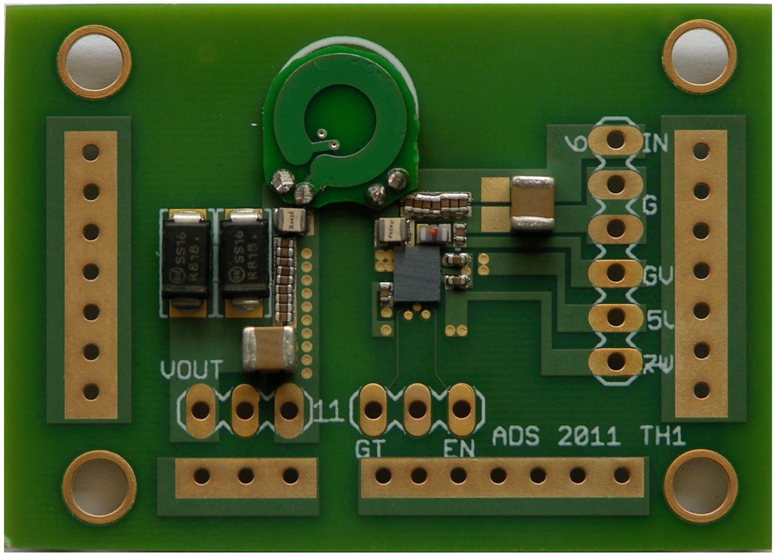




Note: A 1-radius bounding box around the transformer was included in this calculation to capture all the field storage

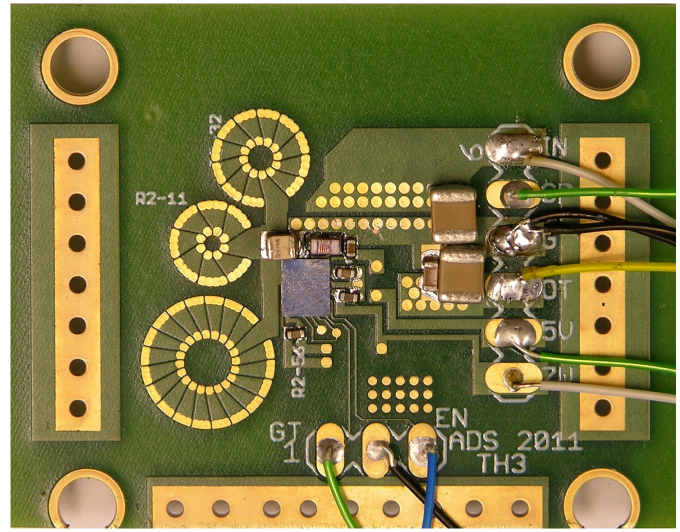
Prototype 75 MHz Integrated Converters

Isolated Φ_2 Converter



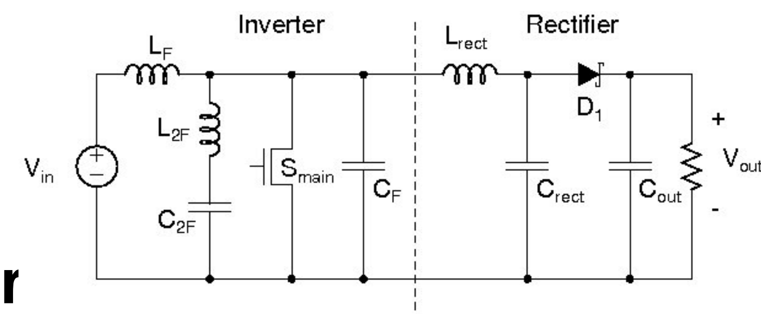
6W, 73% efficiency

Φ_2 Boost Converter



14W, 85% efficiency

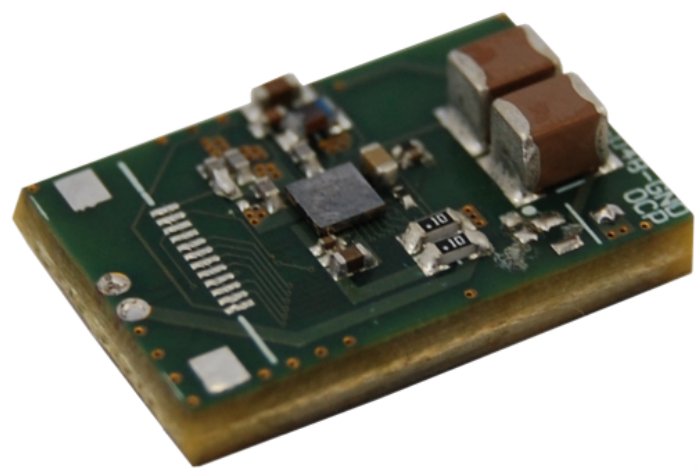
- Non-isolated (boost) variant with PCB-integrated magnetics also demonstrated
- Non-isolated version yields higher power, efficiency, power density
  - Many related topology variants



Pilawa-Podgurski, et. al., "Very High-Frequency Resonant Boost Converters," Trans. P.E. June 2009

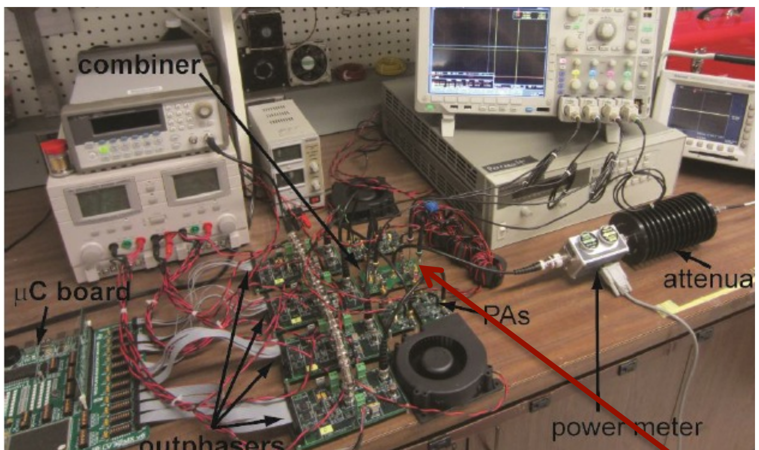
Application of this general approach

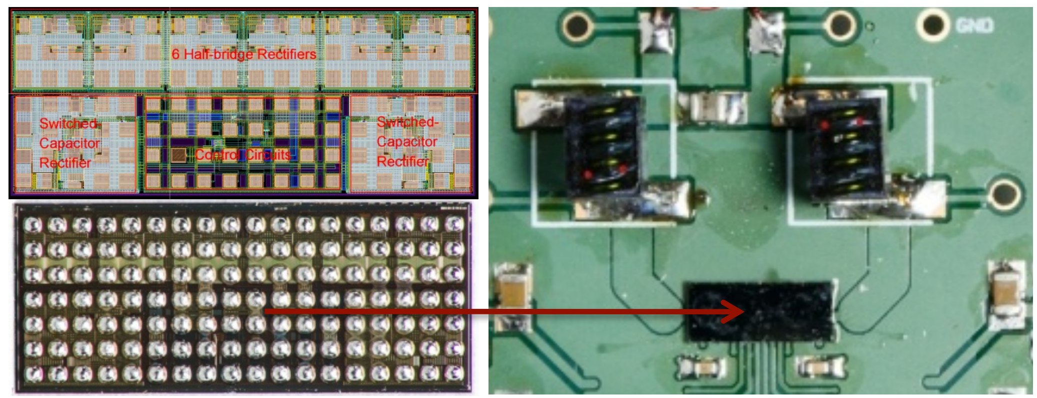
- **VHF LED Driver for MR16 and AR111 Halogen Retrofit**
  - V_{IN}: 12 V_{RMS} ac, 6-19 V dc
  - V_{OUT}: 6 – 21 V dc, 19-36 V dc options
  - P_{OUT}: 10 W (ambient), 25 W (heatsink)
  - Efficiency: to 85% ac-dc, 88% dc-dc
  - -40 C to +120 C ambient operating temperature range
- **Miniaturized, highly integrated with small parts count**
  - Inductors printed in the PCB
  - Form-factor designed to fit in lamp base
  - Small parts count: VHF ASIC + 18 SMT
  - Size: 13 mm x 19 mm x 4 mm
- **Approach can be applied commercially today!**



Many Opportunities for Advances!

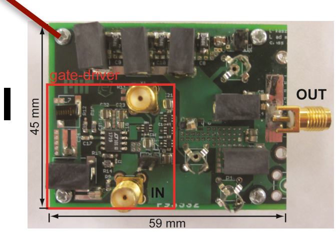
- Improved topologies and control methods
  - Phase-shift control (outphasing) is effective at VHF
    - VHF topologies are often sensitive to load, but with the right design techniques they can be made more flexible
    - Improved performance, power density of inverters, dc-dc converters
  - Synchronous rectification (for higher efficiency at low voltages) is feasible at VHF (especially with CMOS rectifiers)





Integrated 50 MHz CMOS step-down rectifier

27.12 MHz 100 W RF Inverter System with Outphasing Control of 4 inverters



27.12 MHz 25 W GaN Class E Inverter optimized for load modulation and outphasing

A.S. Jurkov, et al, "Lossless Multi-Way Power Combining and Outphasing for High-Frequency Resonant Inverters," *IPEMC 2012*
W. Li et al, *"*Switched-Capacitor Rectifier for Low-Voltage Power Conversion,*" APEC 2013*

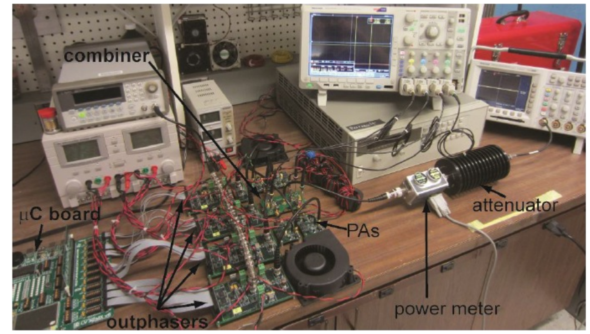
Summary – VHF Power Conversion

- **Higher frequency into the VHF range offers minaturization, integration, bandwidth**
  - Must overcome switching, gating and magnetics losses
  - Must *manage and apply* parasitics
- **VHF conversion is viable TODAY even with existing devices and passives**
  - Converter examples at 10's of Volts and Watts
- **The potential for improvements is large**
  - Improved architectures, topologies and controls can offer major performance gains
  - Improved devices and passive designs also have a big impact
  - *Need to develop processes, devices, passives and packaging that are suited specifically to VHF operation*

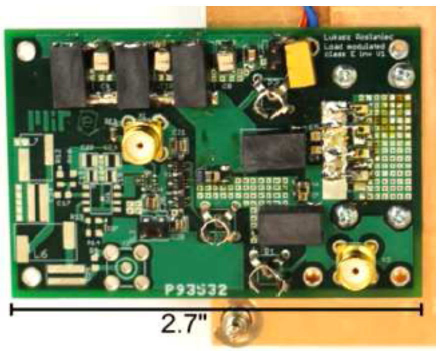
THANK YOU

VHF Power Conversion Work

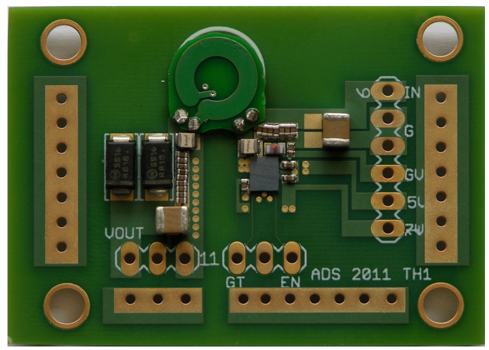
- Applications of VHF power conversion
  - High-power discrete converters
  - Low-power integrated converters
  - dc-dc, ac-dc, dc-ac



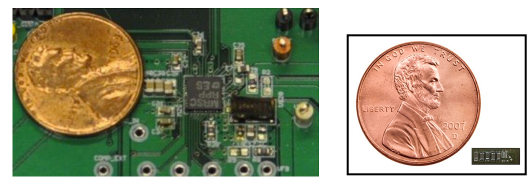
■Outphasing VHF inverter system



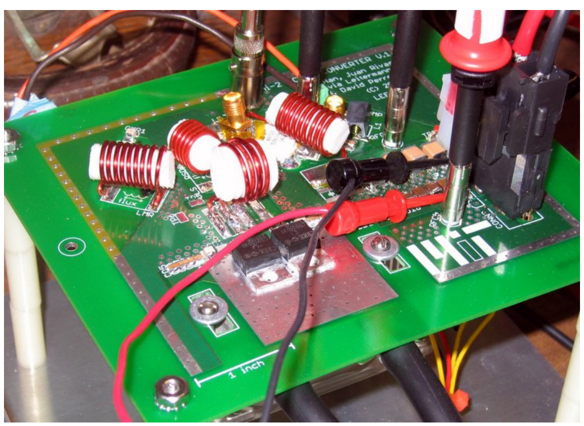
■27.12 MHz GaN resonant inverter for load modulation



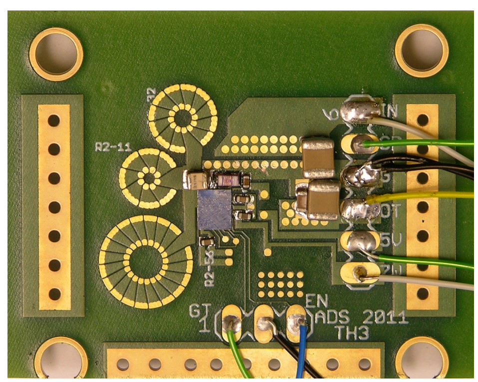
■75 MHz Isolated Converter



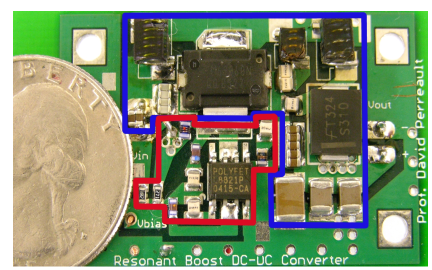
■Two-stage converters for low-voltage power delivery



■Prototype circuit for radar power supply



■VHF Boost Converter with PCB inductors

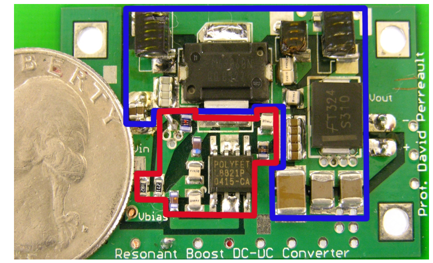


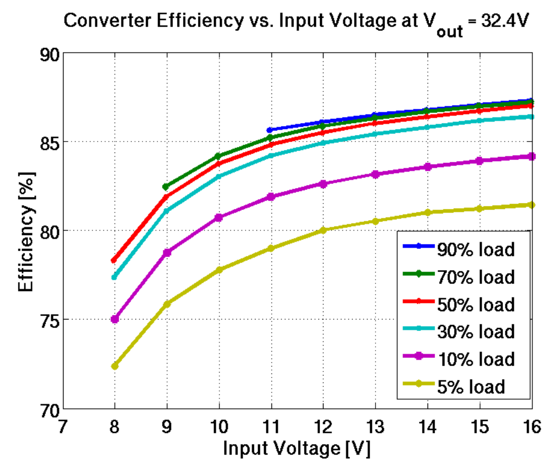
■110 MHz boost converter for automotive applications

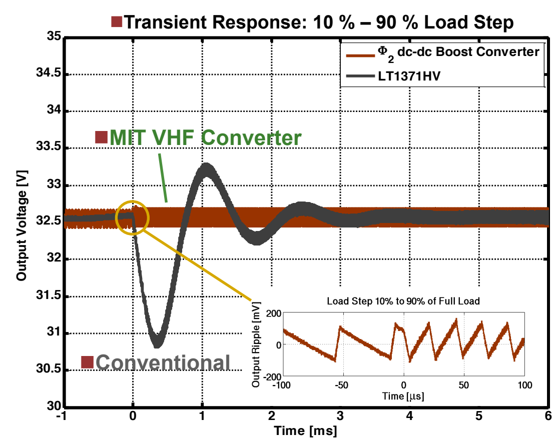
Very High Frequency Power Conversion

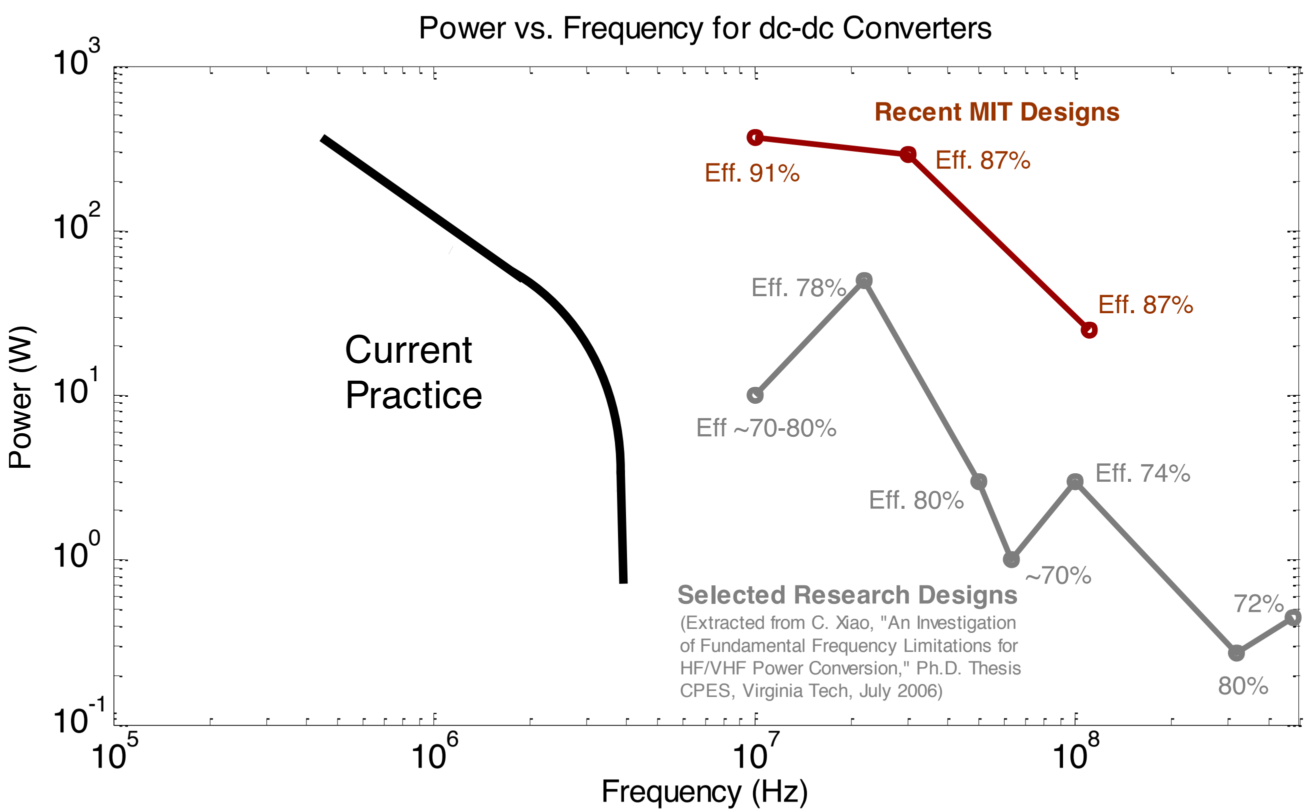
- Seek dramatic increases in power converter switching frequencies into the VHF/UHF range (>30 MHz)
  - Enables miniaturization and integration
  - Provides greatly increased control bandwidth and transient performance

110 MHz dc-dc converter



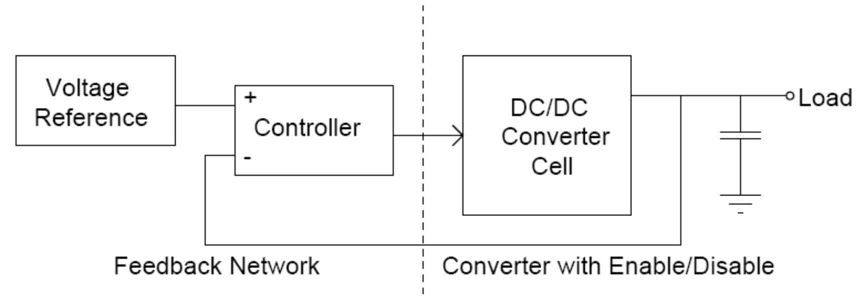




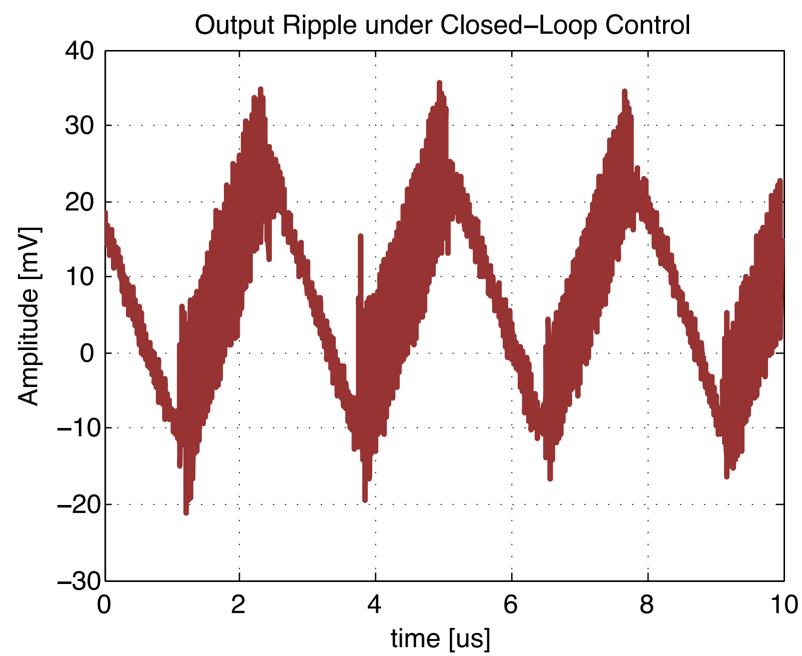


Cell Modulation / On-Off / Burst-Mode Control

- Converter cell "bursts" on and off to regulate output
  - Efficient across wide load range (no loss when cell is off)
  - Cells can operate at narrow load / operating range
    - Fixed frequency and duty ratio
    - Resonant gating, switching at VHF

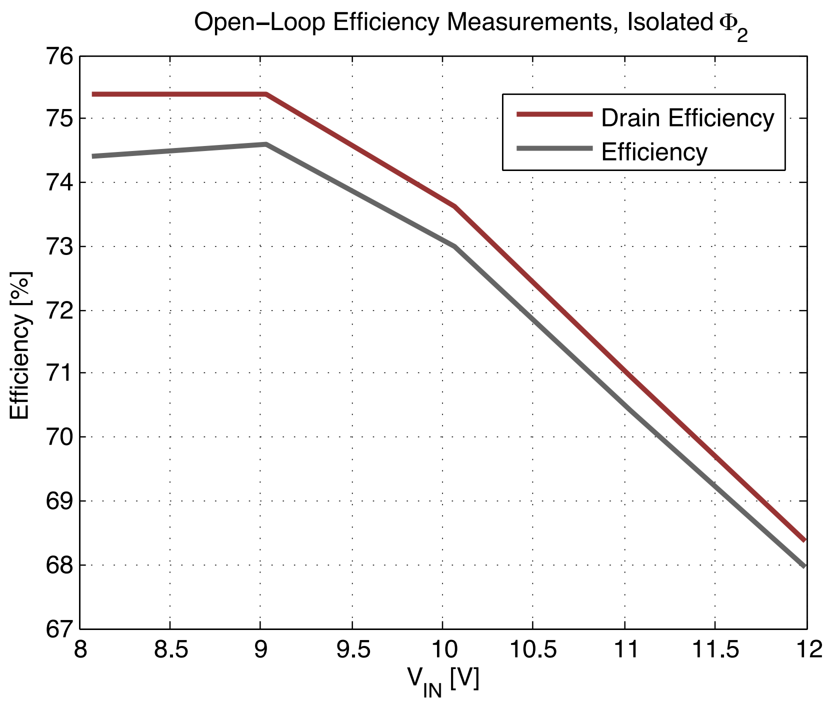


- Power stage components sized for VHF switching frequency (small passives)

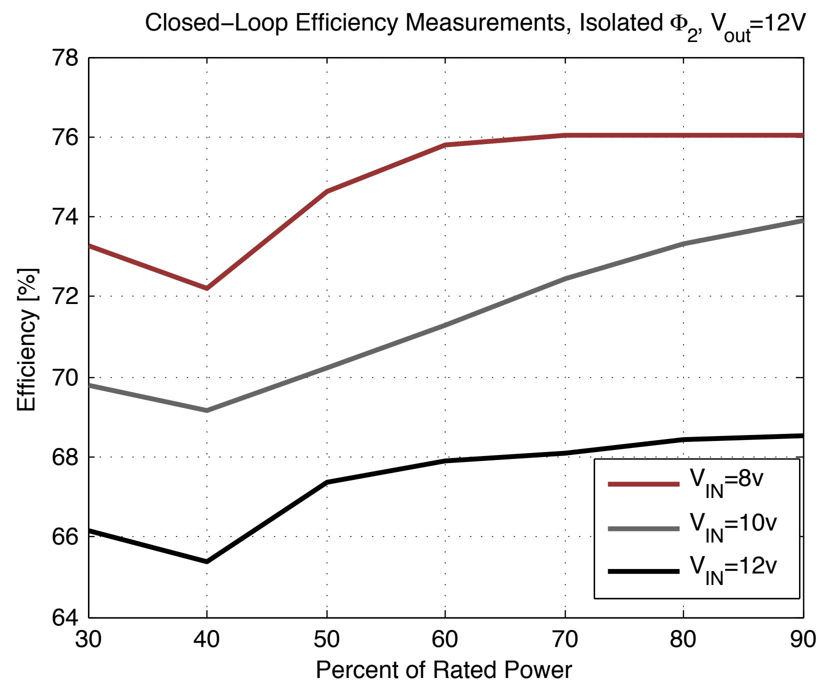


- Input and output filters work at lower modulation frequencies
  - Up to several % of switching freq.
  - But sizing based only on ripple, not transient requirements
  - May use fixed freq. PWM or variable freq. hysteresis modulation

Isolated Φ_2 Efficiency Maps



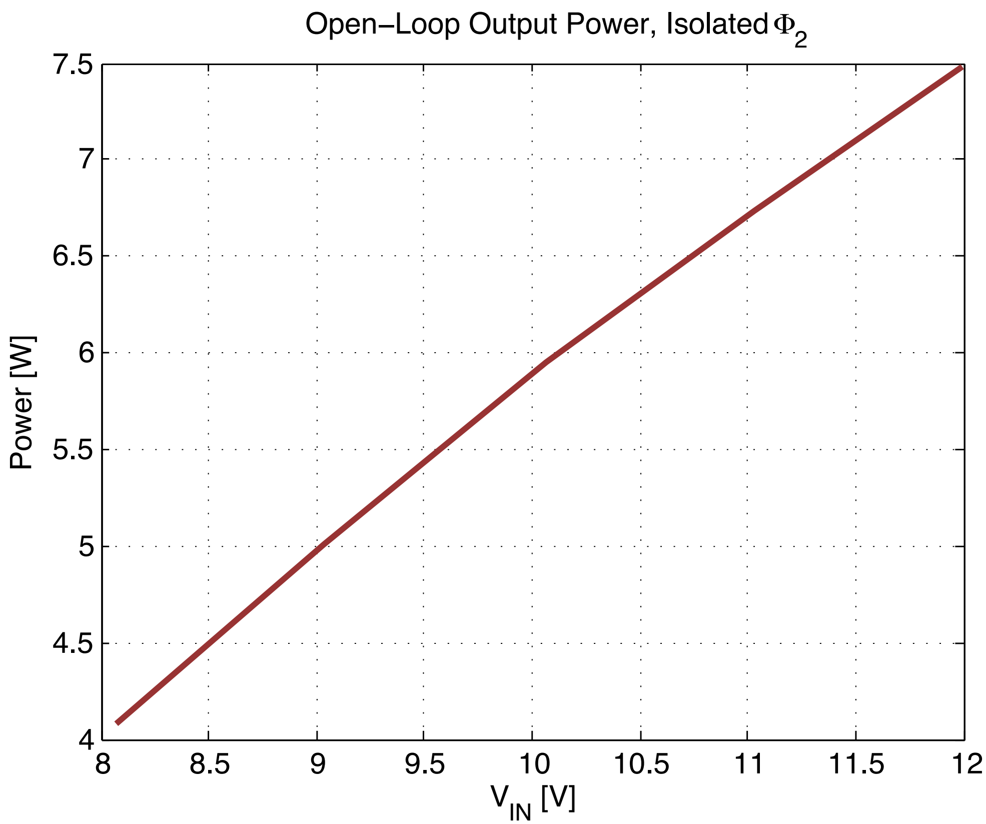
A1 Converter Sample



A2 Converter Sample

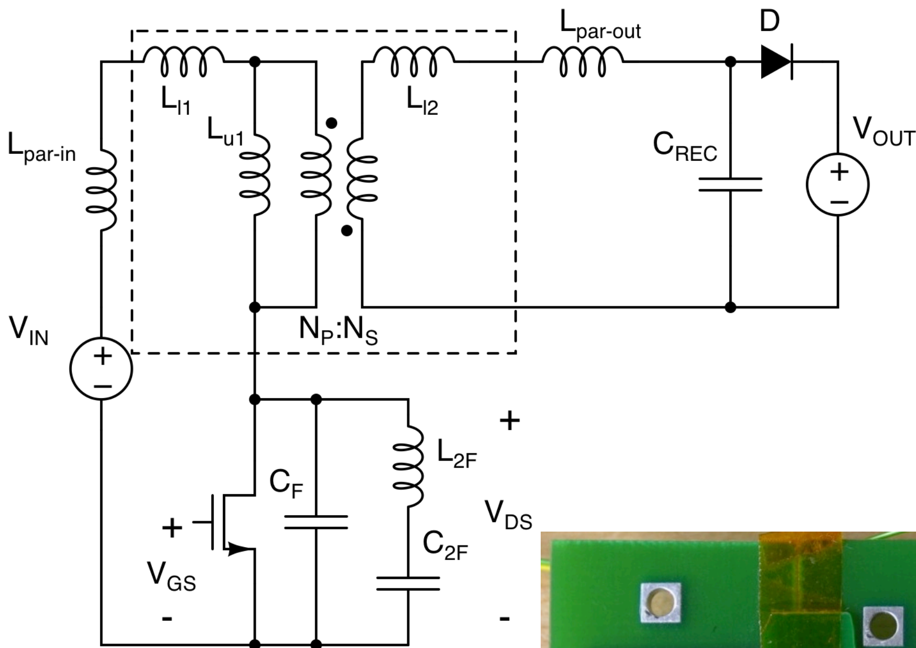
- Gate power costs about 1%
- Modulation costs 1% - 2%

Output Power

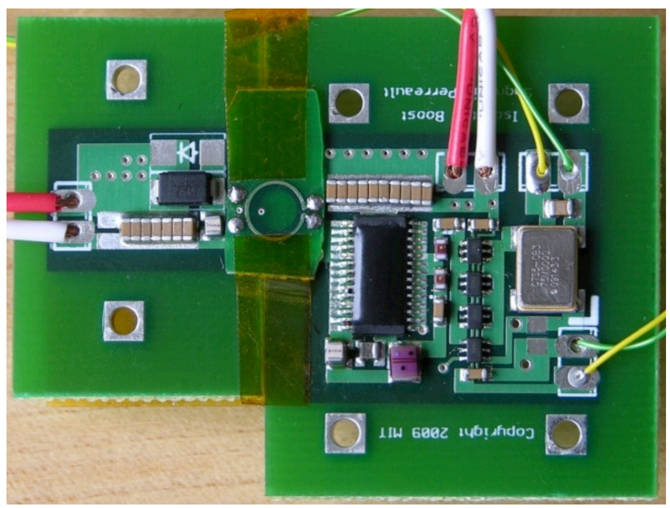


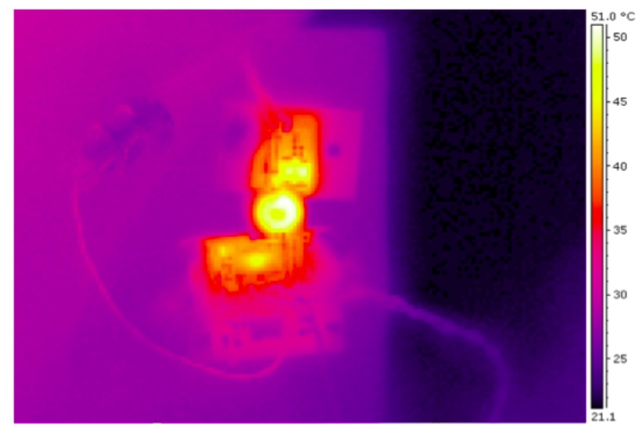
- **Achieves nominal power of 6W**

Isolated Converter Prototype



- **Input voltage: 12 V (nom)**
- **Output voltage: 12 V (nom)**
- **Output power: 7 W (nom)**
- ***f_{SW}*: 75 MHz**
- **Efficiency ~ 74%, 94% (xformer)**



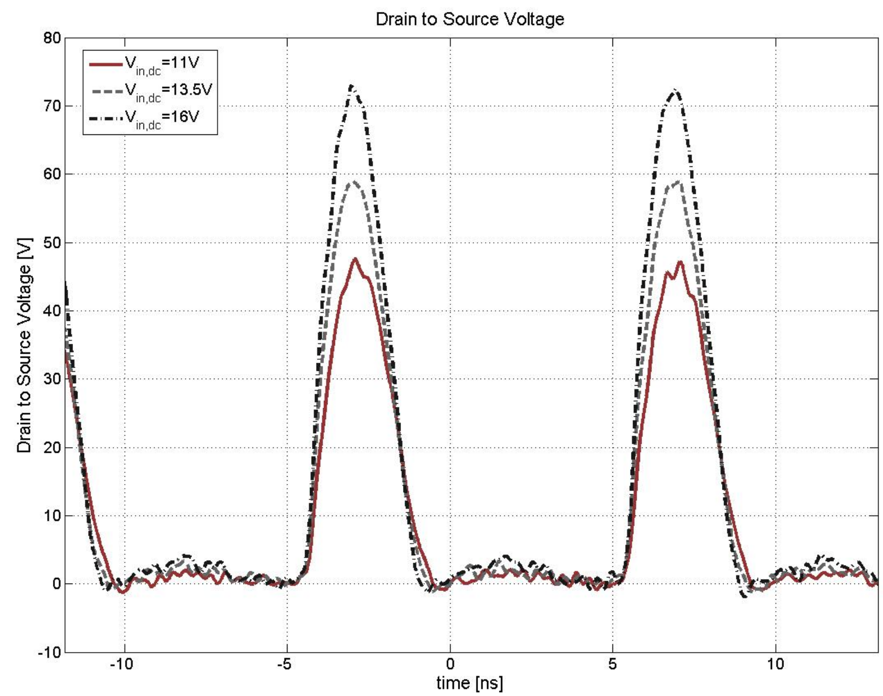


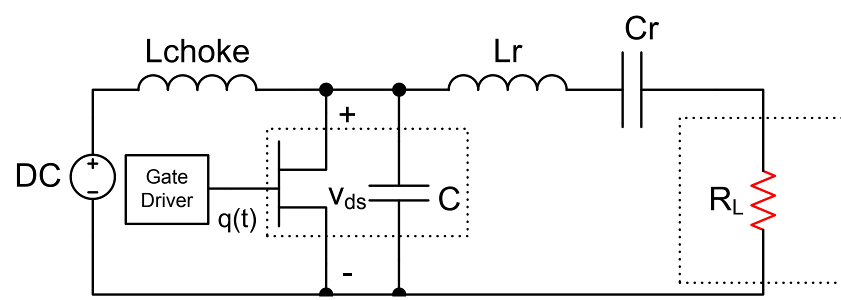
Limitations of Traditional Class E Inverter

- High device stresses
  - $V_{ds,pk} \approx 3.6 \cdot V_{IN}$ for Class-E
- Uses a large "choke" inductor
  - Constrains on/off control
- Highly sensitive to load variation
  - Constrains operating range
- Highly constrained design in terms of device parameters
  - Tight link between output power, device capacitance, loss, and frequency

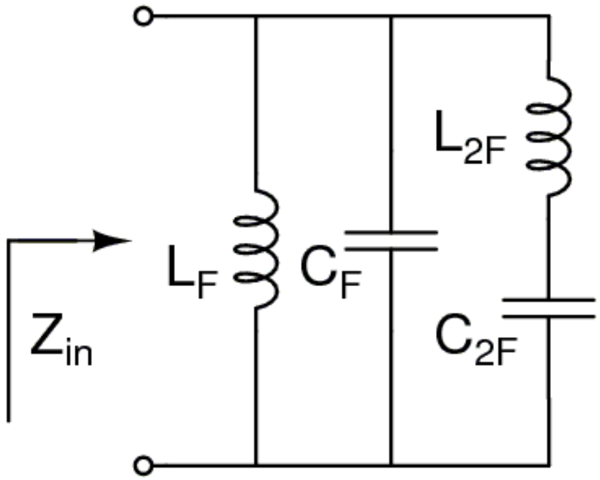
$$P_{out} \propto C_{oss} \cdot f \cdot V_{DC}^2$$

$$\%P_{cond} \propto R_{ds-on} \cdot C_{oss} \cdot f$$





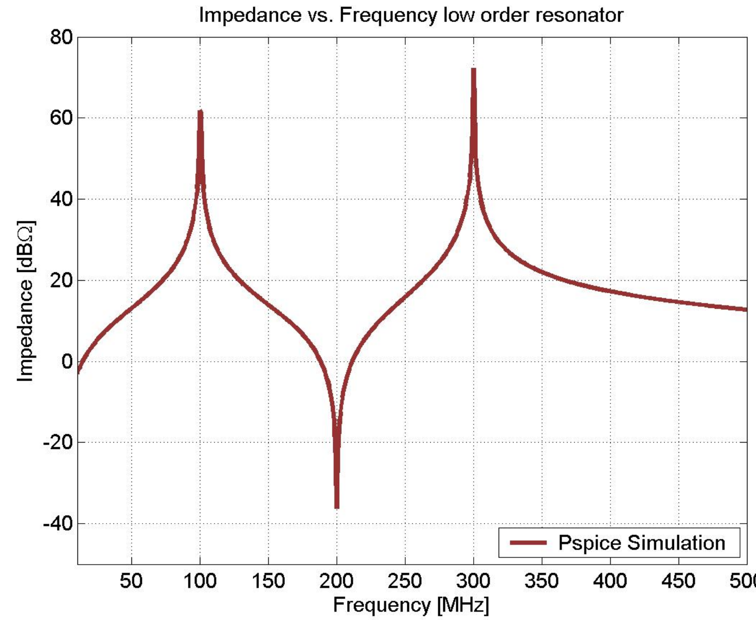
Impedance-Based Waveform Shaping



$$L_f = \frac{1}{9(\pi \cdot f_s)^2 C_f}$$

$$C_{2f} = \frac{15}{16} C_f$$

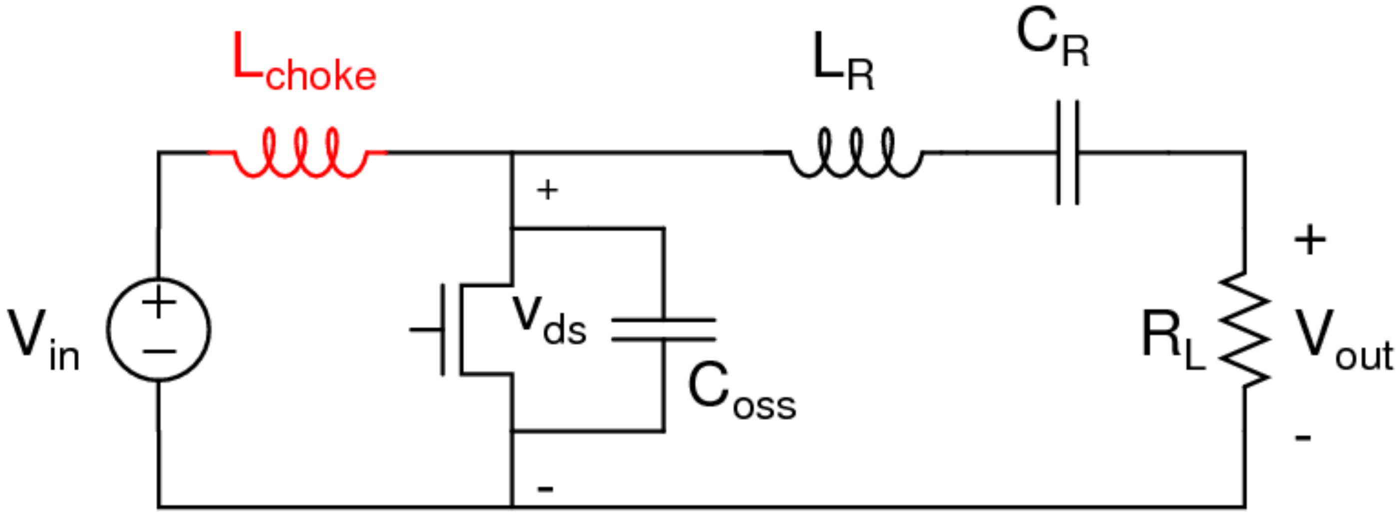
$$L_{2f} = \frac{1}{15(\pi \cdot f_s)^2 C_f}$$



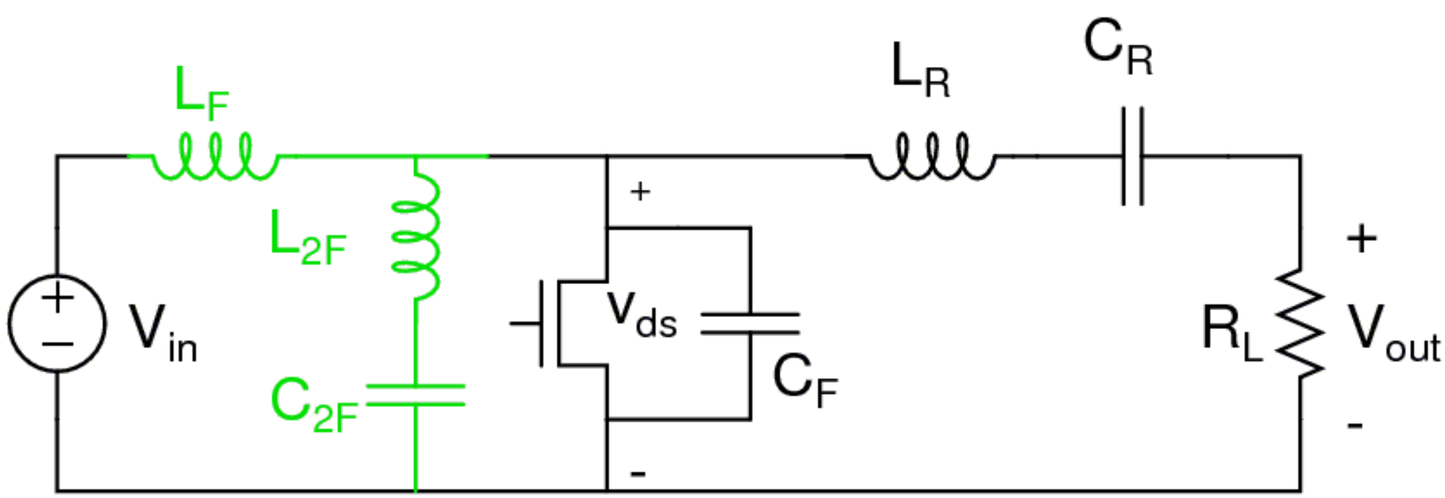
- By controlling the impedance seen at the transistor output, we can shape the voltage waveform
- A simple network can null the second harmonic and present a high impedance at the fundamental and the third harmonic
  - Impose odd-harmonic symmetry in voltage waveform
- This network can be used in an inverter to “shape” the switch voltage to approximate a trapezoidal wave

Class E --> Φ2 Inverter

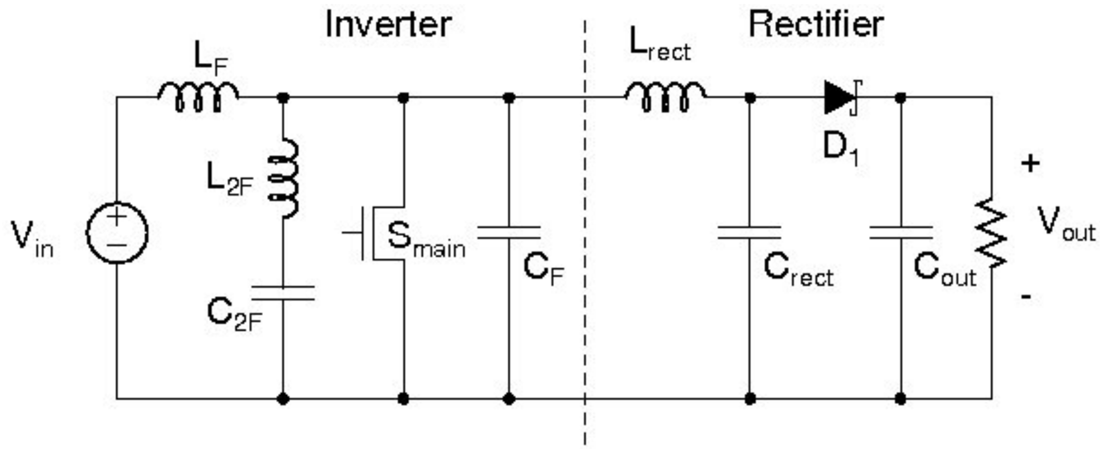
- Class E Inverter

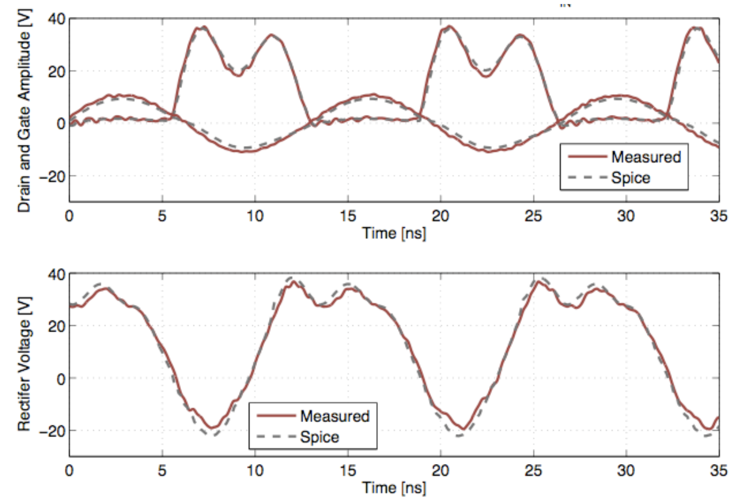


- Φ2 Inverter



Resonant Φ_2 Boost Converter

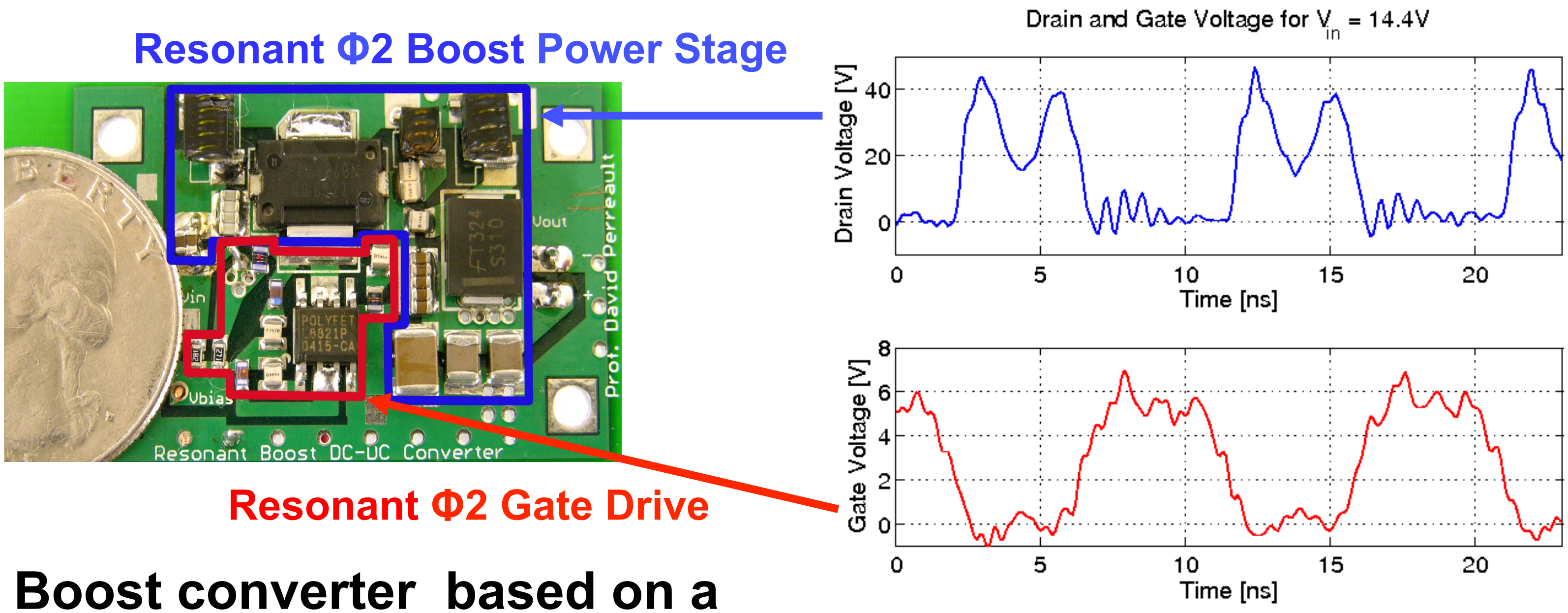




- Replace inverter load network with resonant rectifier
  - Rectifier tuned to replace load network at fundamental
  - Provides dc current transfer from input to output (similar to a conventional boost converter)
- Low peak stress, ground-reference switch
- Fully resonant with small component size
- Ideally suited for constant frequency/duty ratio operation
- Low energy storage - good candidate for on/off modulation control

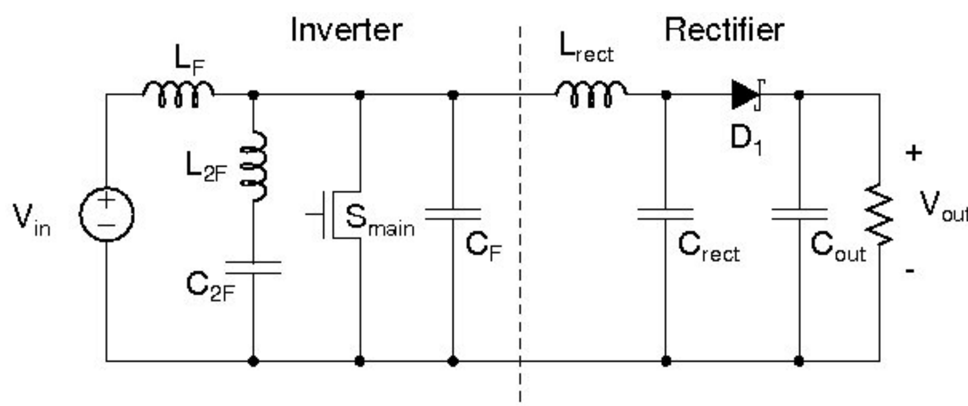
Pilawa-Podgurski, et. al., "Very High-Frequency Resonant Boost Converters," Trans. P.E. June 2009

Φ_2 Boost – Discrete Implementation



Φ_2 Boost converter based on a commercial LDMOSFET

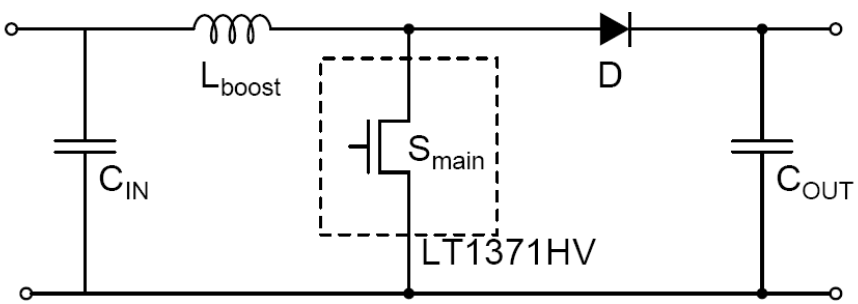
- Switching Frequency: 110 MHz
- Input voltage range: 8V – 18V
- Output voltage range: 22 – 34V
- Output power 23 W nominal
- Hysteretic On-off control
- Small inductors, potential for integration or self-shielding design



Pilawa-Podgurski, et. al., "Very High-Frequency Resonant Boost Converters," Trans. P.E. June 2009

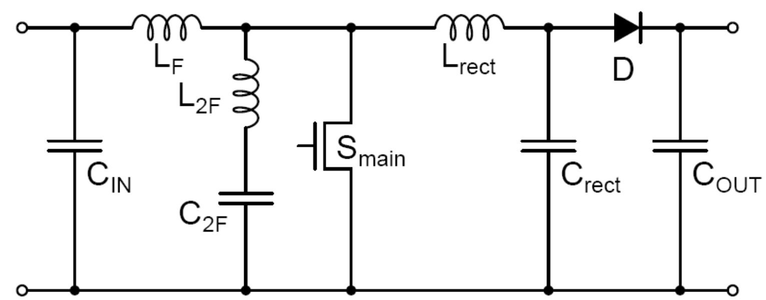
Comparison to Conventional Converter

Conventional Boost @ 500 kHz



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

Φ_2 Resonant Boost at 110 MHz



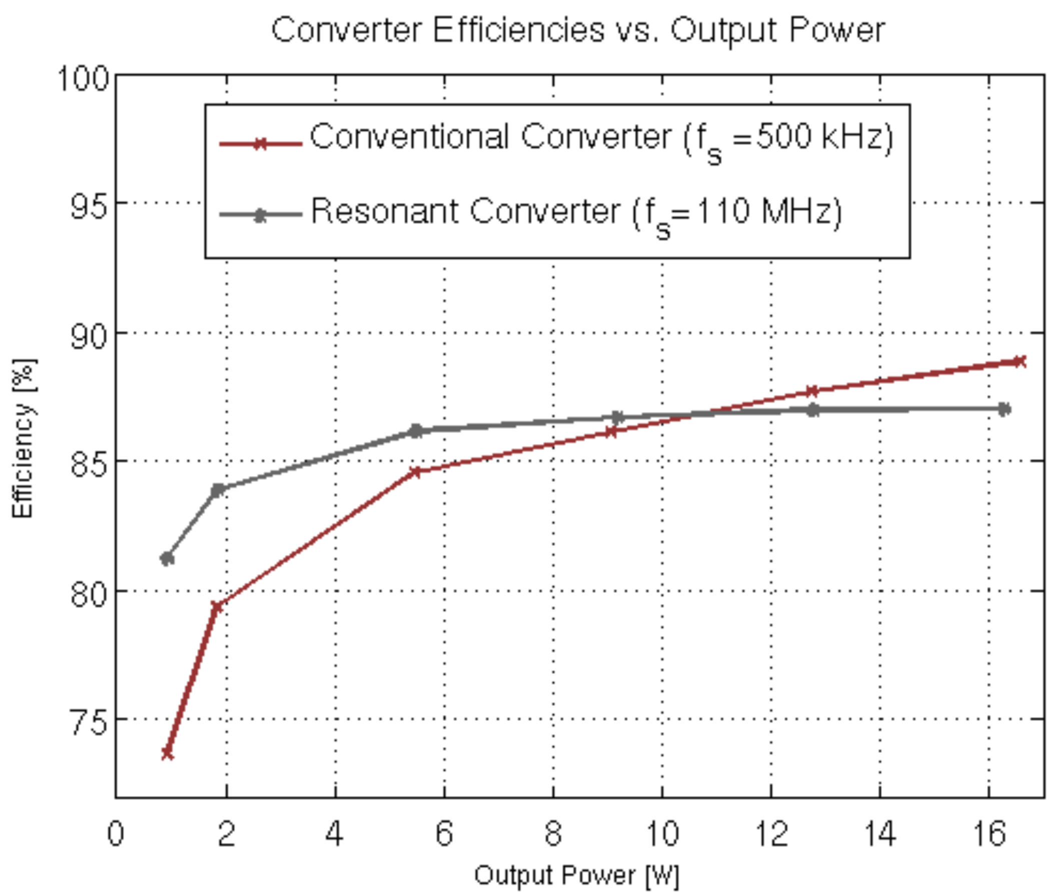
Component	Value	Type
L_F	33 nH	Coilcraft 1812SMS
L_{2F}	12.5 nH	Coilcraft A04TG
L_{rect}	22 nH	1812SMS
C_{2F}	39 pF	ATC100A
C_{rect}	10 pF	ATC100A
C_{out}	75 μF	Multilayer Ceramics
C_{in}	22 μF	Multilayer Ceramics
S_{main}		Freescale MRF6S9060
D		Fairchild S310

Single inductor, 10 μH

3 inductors, largest 33 nH

Comparison made with the same input and output capacitance

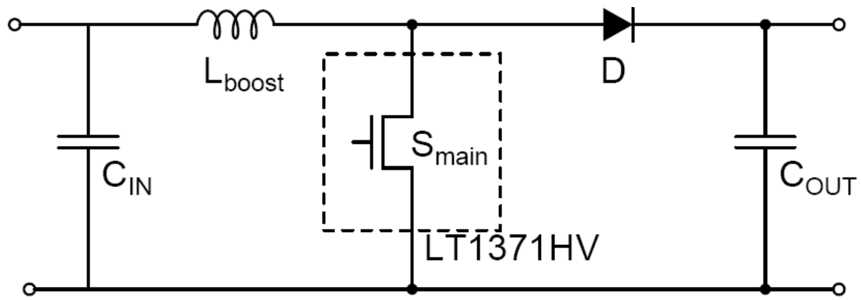
Comparison to Conventional Converter

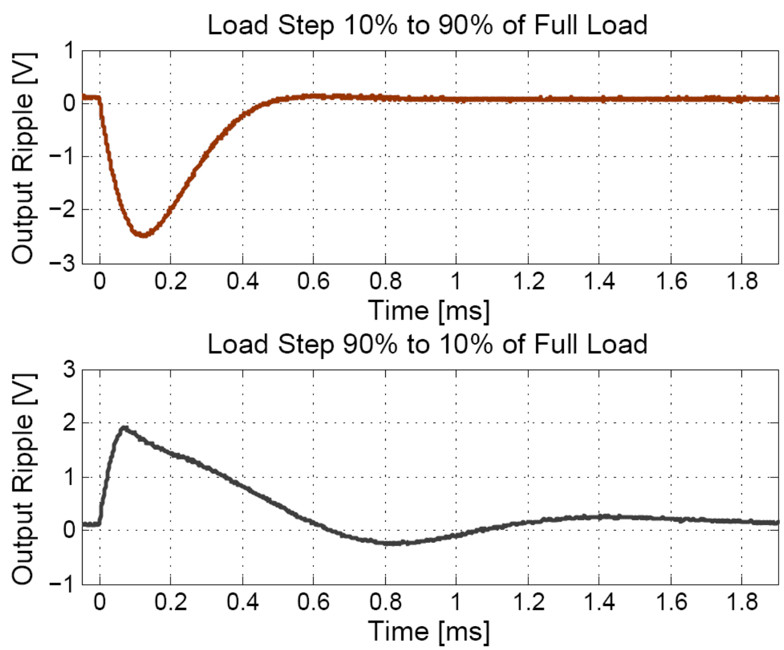


- Converter efficiencies are similar except at light load
  - Conventional PWM converter slightly more efficient at full load (~2%)
  - Resonant converter with on/off control more efficient at light load (~9%)

Comparison to Conventional Converter

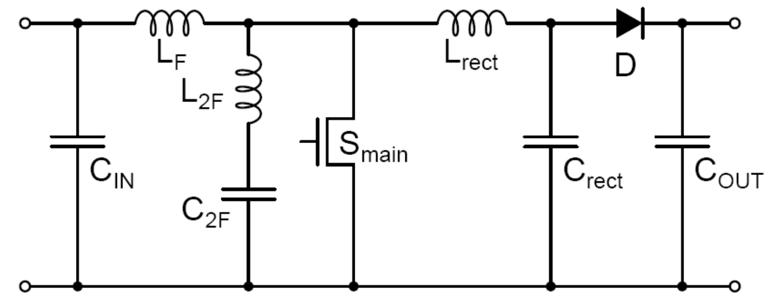
Conventional Boost @ 500 kHz

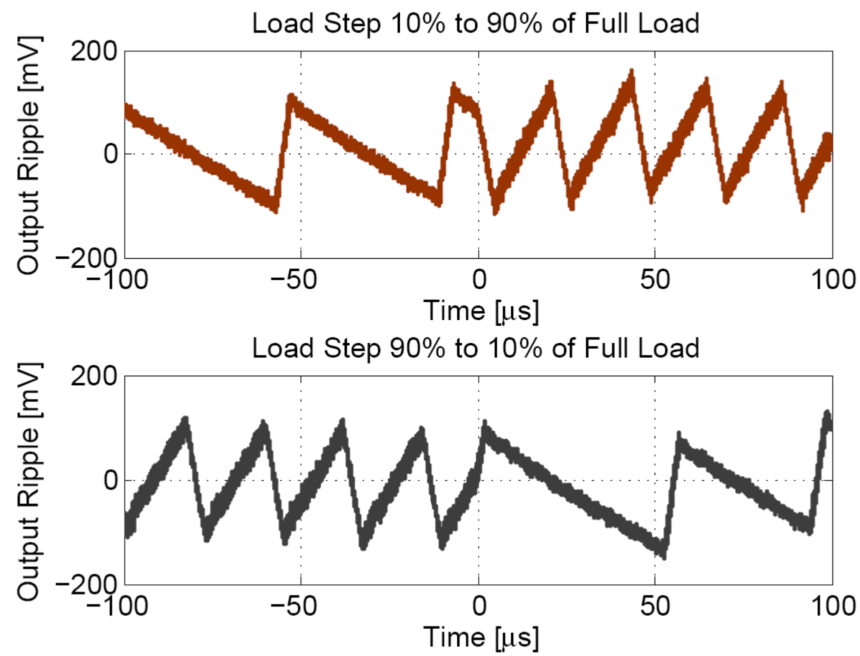




Steady-state ripple 10 mV$_{pp}$
Transient response to 2.5 V, 2 ms

Φ_2 Resonant Boost at 110 MHz

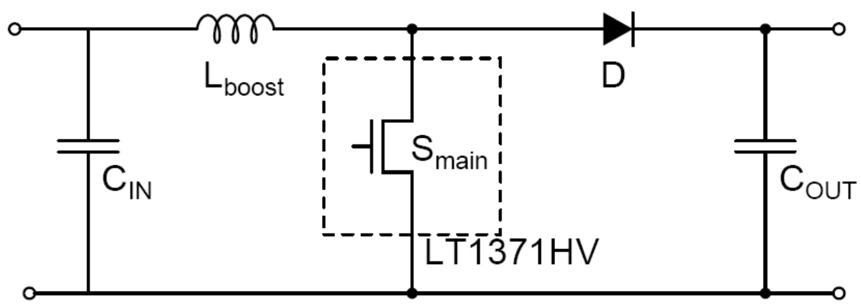




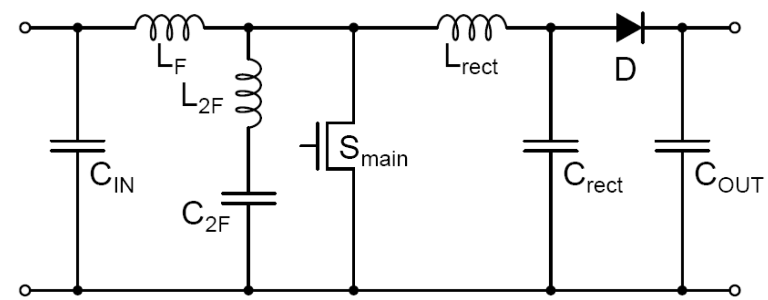
Steady-state ripple 200 mV$_{p-p}$
Transient response < 200 mV, 1 µs

Comparison to Conventional Converter

Conventional Boost @ 500 kHz



Φ_2 Resonant Boost at 110 MHz

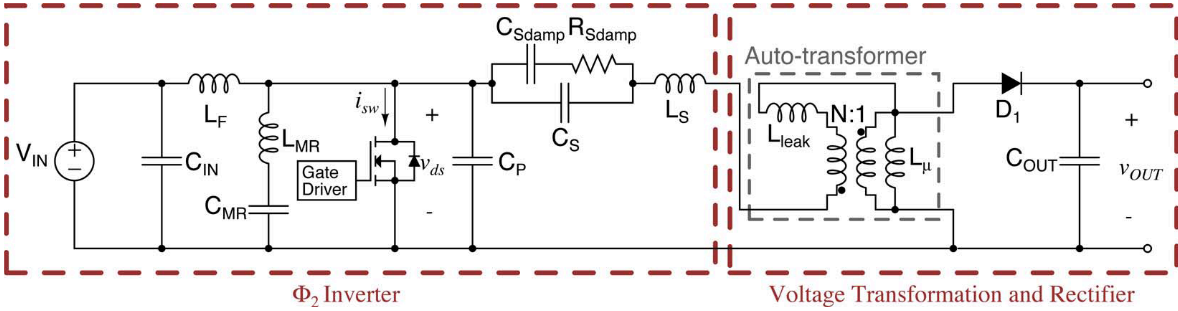


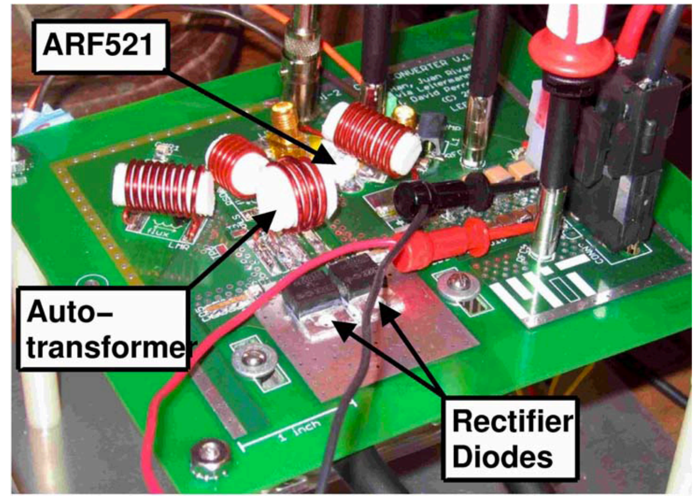
Comparison with identical input and output capacitance

	Conventional (500 kHz)	*Resonant (110 MHz)*	**Change**
Inductor volume (mm^3)	831	187	-78 %
Capacitor volume (mm^3)	240	266	+11 %
Passives volume (mm^3)	1071	453	**-58 %**

- **With identical input and output capacitance, the VHF design reduces magnetics volume by 78% and total passives volume by 58%**
  - **Further increases in frequency are viable and would further increase the advantage of VHF conversion**
- **To provide similar transient performance, the conventional converter volume would have to be increased by >> 10X !**

High-voltage Φ_2 dc-dc Converter

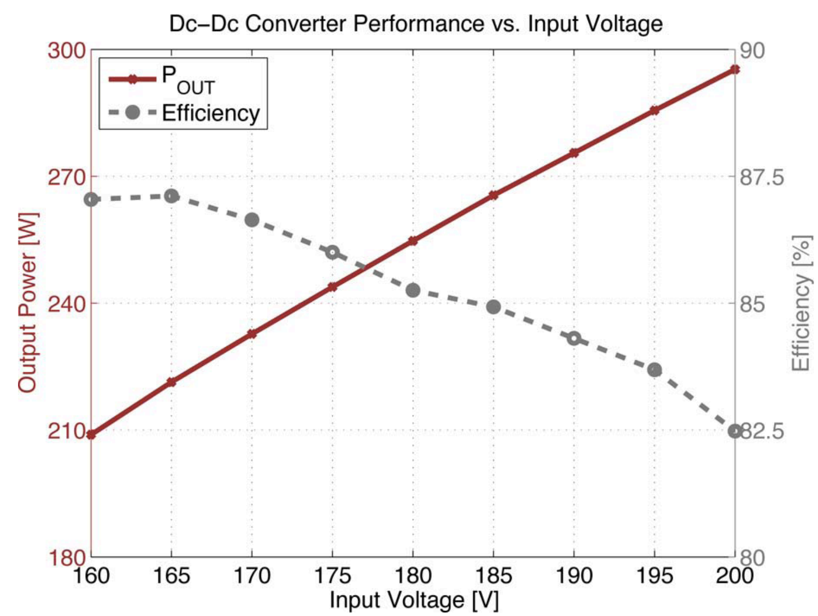




Isolated Φ_2 converter: large step down from high-voltage input

30 MHz, 200 W, 200 V, ~85% efficient

- Switching Frequency: 30 MHz
- Output power: 200 W nominal
- Efficiency ~ 85%
- Input voltage range: 150V – 200V
- Output voltage: 33 V nominal
- Resonant gate drive (not shown)
- Hysteretic On-off control



Rivas, et. al., "A Very-High Frequency dc-dc Converter based on a Class Phi-2 Resonant Inverter," Trans. P.E. Oct., 2011

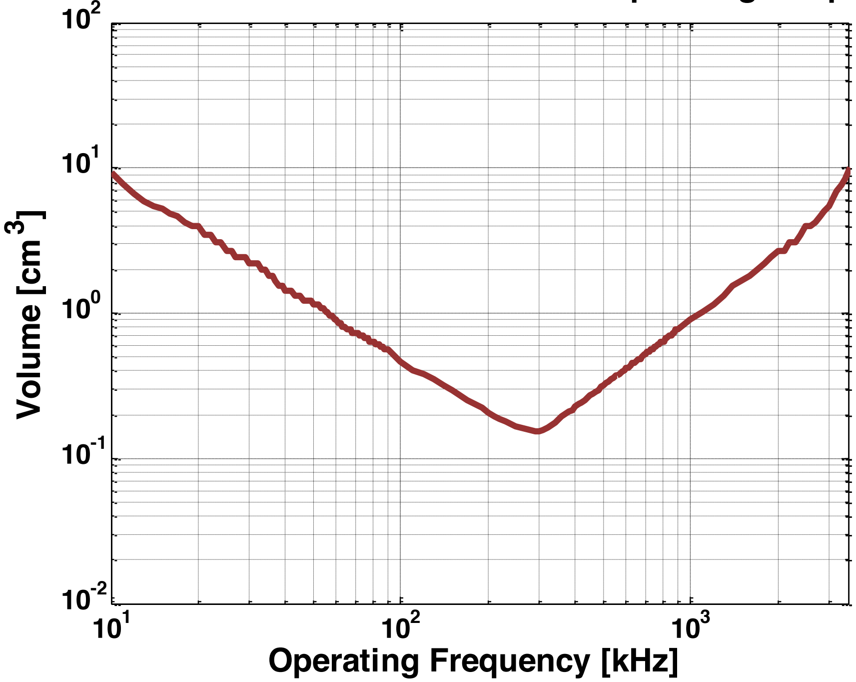
Coreless Resonant Inductors

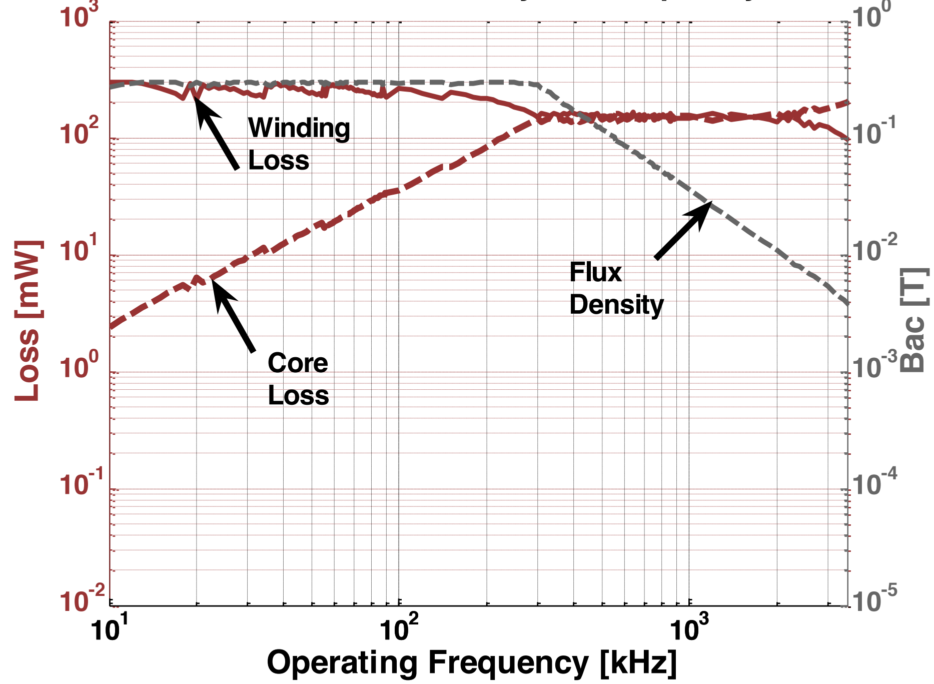
- Because of core loss, there is a fundamental frequency limit associated with minimizing size in resonant cored magnetics

- In the VHF operating regime, coreless inductors can generally achieve a better tradeoff between Q and volume

- How do coreless inductors scale with frequency?

Cored Resonant Inductors

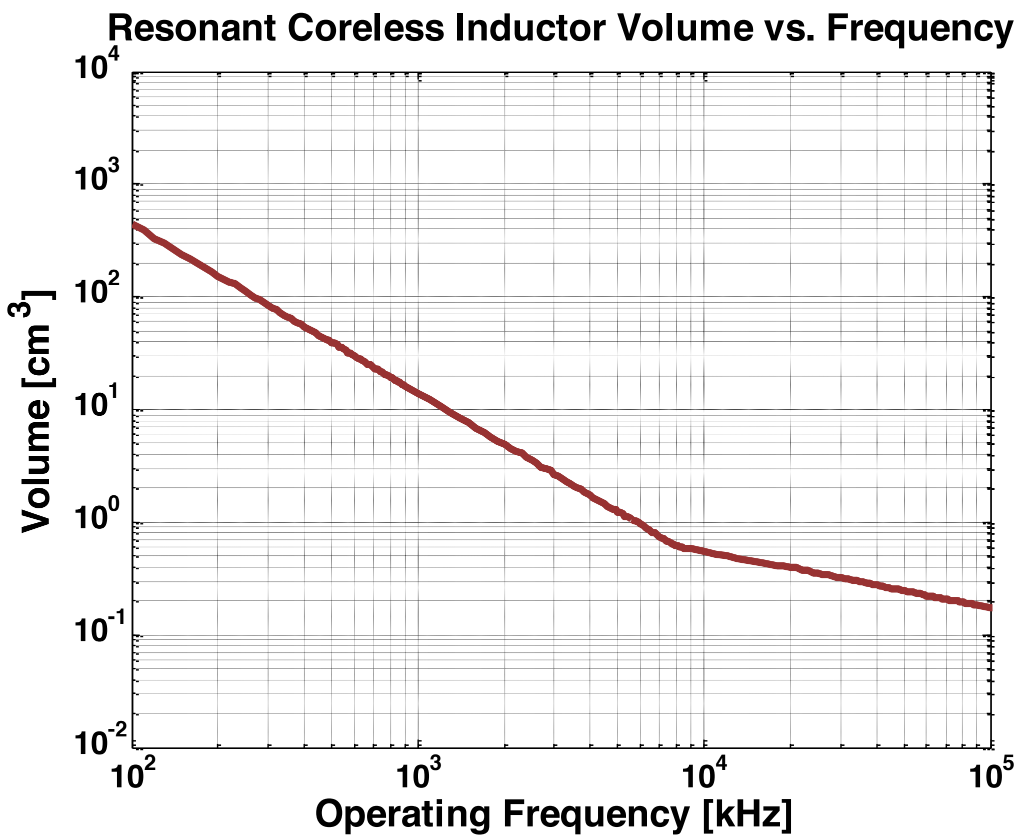




- Physical size based on
  - Flux density limits
  - Loss/efficiency requirements
    - Quality factor
  - Thermal limits
    - Heat transfer

- At low frequencies: increases in frequency reduce energy storage requirements
  - Core size decreases with frequency
- At high frequencies: core loss requires reductions in flux density to meet loss and/or temperature limits
  - Core size increases with frequency

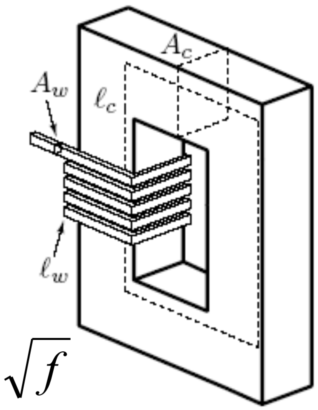
Coreless Resonant Inductor Scaling



- At constant η (constant *Q*): Volume proportional to $f^{-3/2}$
- At constant heat flux: Volume proportional to $f^{-1/2}$ with *Q* improving as $f^{1/3}$

Coreless magnetics always improve with frequency!

Coreless Resonant Inductors



- In general, the inductance scales with linear dimension factor ε with the following relation

$$L = \frac{N^2 \mu A_L}{l} \propto N^2 K \varepsilon$$

- For a 1-turn inductor, $L = K_1 \varepsilon, R_{DC} = \frac{\rho l}{A_w} = \frac{K_2}{\varepsilon}, R_{AC} = \frac{d}{\delta} R_{DC} = K_3 \sqrt{f}$

- Exchange 1-turn for N turns,

$$L = N^2 K_1 \varepsilon, R_{DC} = \frac{N^2 K_2}{\varepsilon}, R_{AC} = N^2 K_3 \sqrt{f}$$

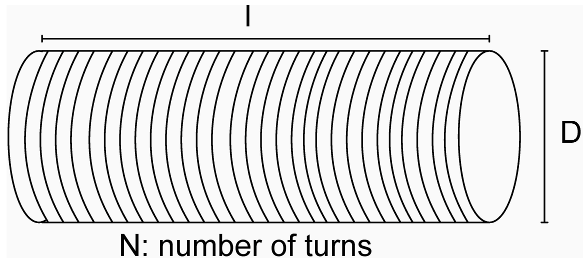
- Q is related to linear dimension scaling factor ε and frequency,

$$Q = \frac{2\pi f L}{R_{AC}} = \frac{2\pi f N^2 K_1 \varepsilon}{N^2 K_3 \sqrt{f}} = K_4 \varepsilon \sqrt{f}$$

- In order to maintain constant Q / loss across frequency,

$$\varepsilon \propto \frac{1}{\sqrt{f}}, Volume \propto \varepsilon^3 \propto \frac{1}{\sqrt{f^3}}$$

Coreless Resonant Design Example



- **For a single-layer coreless solenoid inductor, the inductor Q can be estimated based on Medhurst's work:**

$$Q \approx 7.5 D\psi\sqrt{f}, \psi_{OPTIMUM} = 0.96\tanh(0.86\sqrt{\frac{l}{D}})$$

- **To optimize Q, keep inductor form factor at** $\frac{l}{D} = 5, \psi_{OPTIMUM} \approx 0.88$
- **At constant Q, the volume required scaled with** $f^{-3/2}$
  - **until the number of turns gets down to 1**

$$Q \approx 6.6D\sqrt{f}, D = \frac{Q}{6.6\sqrt{f}}$$

$$Volume = \frac{1}{4}\pi D^2 l = \frac{5}{4}\pi D^3 = \frac{5}{4}\frac{\pi}{6.6^3}\frac{Q^3}{f^{3/2}}$$

- ***Note that heat transfer may limit size in addition to loss***

Scaling of Coreless Designs at Constant Heat Flux

- **From the thermal model, imposing a temperature limit is equivalent to limiting heat flux through the inductor surface**
  - **Surface area** $\propto \varepsilon^2$
- **From previous discussion, Q is related to linear dimension scaling factor** ε **and frequency by**

$$Q = \frac{2\pi f L}{R_{AC}} = \frac{2\pi f N^2 K_1 \varepsilon}{N^2 K_3 \sqrt{f}} = K_4 \varepsilon \sqrt{f}$$

- **Temperature rise is then related to scaling factor** ε **and frequency via**

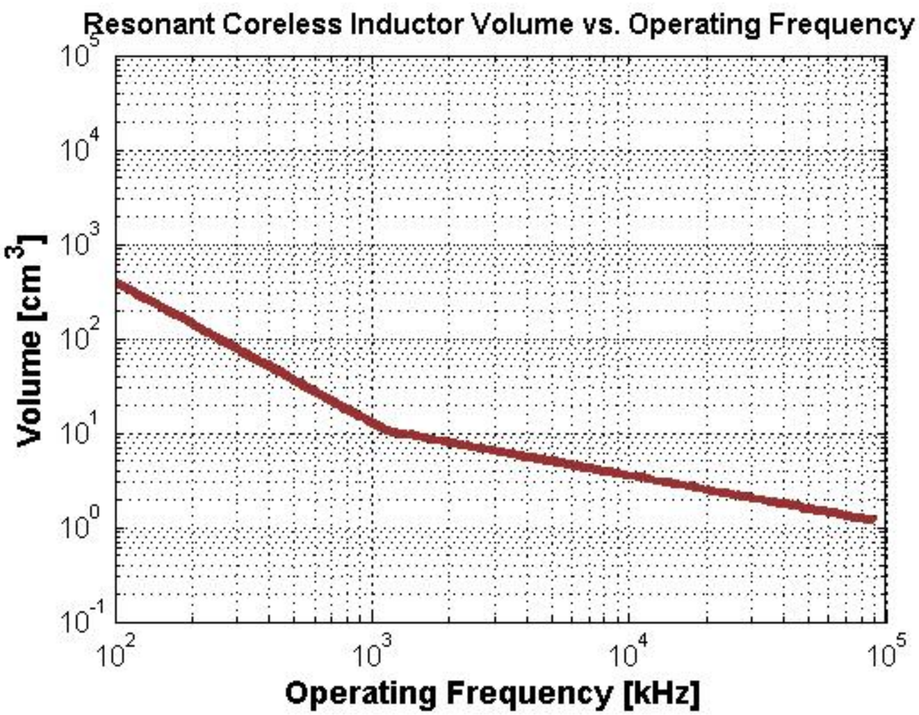
$$\Delta T = k \frac{P_{diss}}{Area_{Surface}} = \frac{k}{Area_{Surface}} \frac{I_{RMS}^2 Z}{Q} = k_2 \frac{I_{RMS}^2 Z}{\varepsilon^3 \sqrt{f}}$$

- **At the temperature rise limit (constant heat flux), the volume scales with** $f^{-1/2}$
  - **With Q improving as** $f^{1/3}$***:***

$$Q = K_4 \varepsilon \sqrt{f}, \varepsilon \propto f^{-1/6}, Q = K_5 f^{-1/6} f^{1/2} = K_5 f^{1/3}$$

Coreless Resonant Inductor Scaling

- CAD optimization of solenoid inductors using Medhurst's formulation:



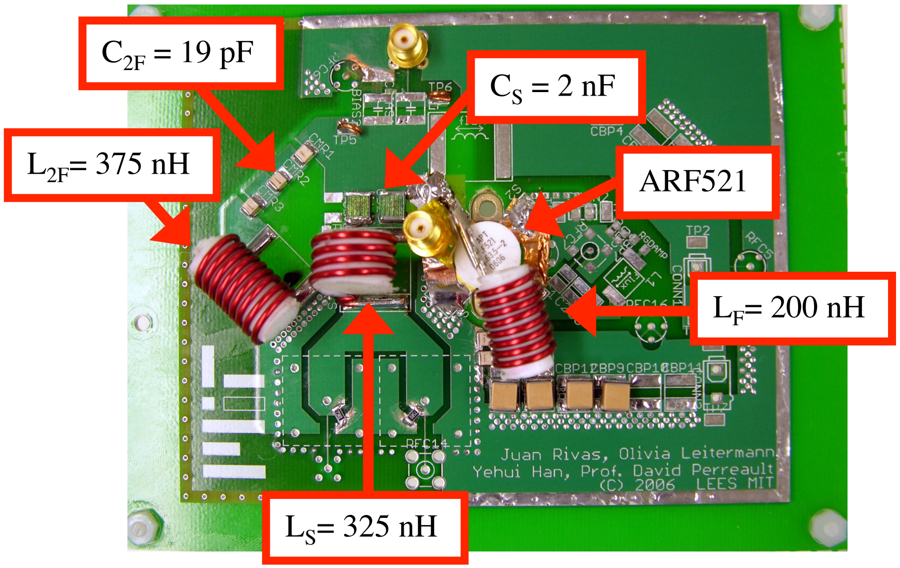
- Example:
- Inductor Volume with Q and temperature limitation
- 1.6uH @ 1MHz
- IAC = 0.7A
- Q_{min} = 100
- ΔT_{max} = 75 °C

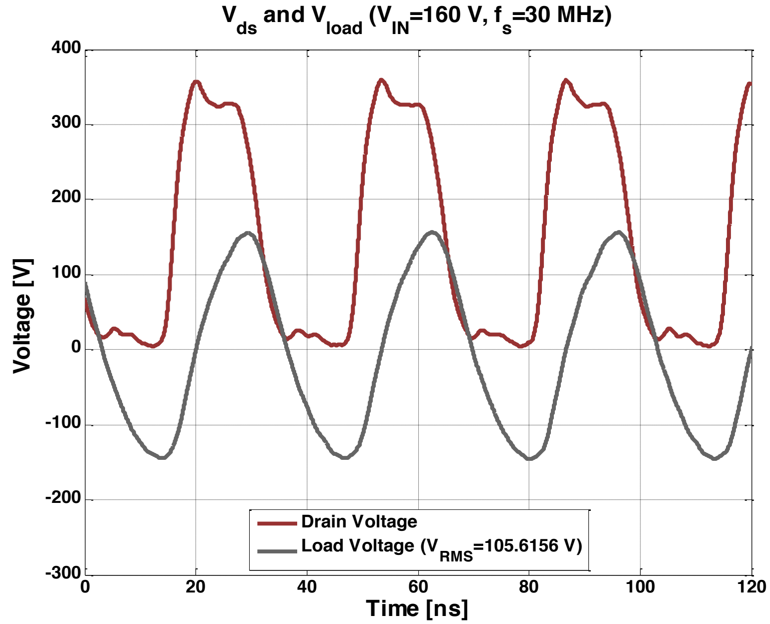
- Impose minimum Q and maximum temperature rise requirement
- Initially, the inductor volume falls off with $f^{-3/2}$
- When temperature rise becomes the limitation factor, the inductor volume falls off with $f^{-1/2}$

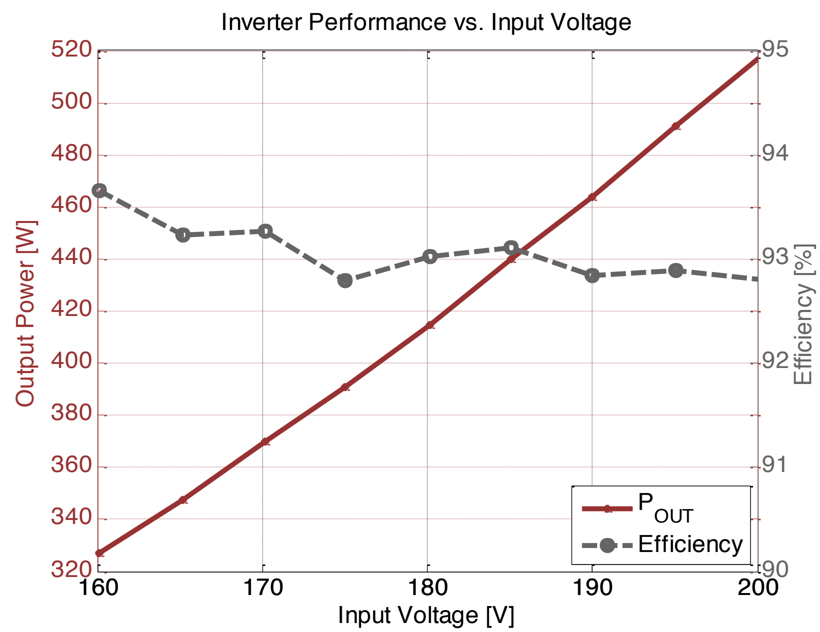
Magnetics Design Summary

- Limited by percentage power loss and temperature rise, inductor volume scales across frequency in the following ways
  - There is a fundamental frequency limit achievable with cored inductors, inductor volume increases significantly as its operating frequency approaches VHF regime
  - Volume of Coreless Resonant inductor vs. frequency
    - At constant η (constant *Q*): Volume proportional to $f^{-3/2}$
    - At constant heat flux: Volume proportional to $f^{-1/2}$ with *Q* improving as $f^{1/3}$

Example Φ2 Inverter Design



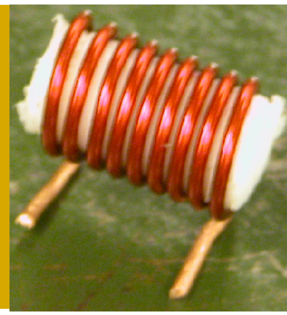
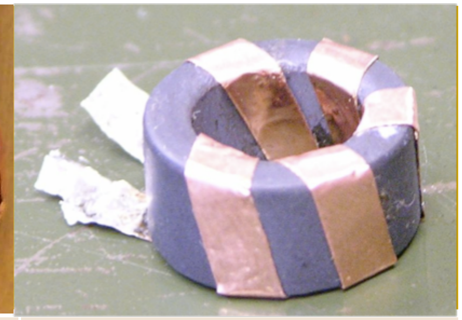




- 30 MHz class Φ2 inverter
  - V_{in} = 160 – 200 V
  - P_{out} > 320 W @ η_D~ 93%
- Breaks class E frequency limit
- Low device stress
  - $V_{ds,pk}$ < 2.3 V_{in}
- Small passive components
  - Fast transient response

Cored magnetics at VHF frequencies

- Some low permeability and high frequency (>10MHz) magnetic materials are available:

			
Type	Solenoid coreless	Toroid Coreless	Toroid Magnetic core
Inductance	200 nH	217.6 nH	190 nH
Volume	1.0 cm^3	1.2 cm^3	0.5 cm^3
Q_L	88	98	120

Inductors Designed at 30 MHz and 1 A Current Level

With the right materials/designs we can still leverage cored magnetics at frequencies to ~ 100 MHz