IEEE PELS Workshop on Emerging Technologies:
Wireless Power (2018WoW)

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Dual-Band Multi-Receiver Wireless Power Transfer with Reactance Steering Network

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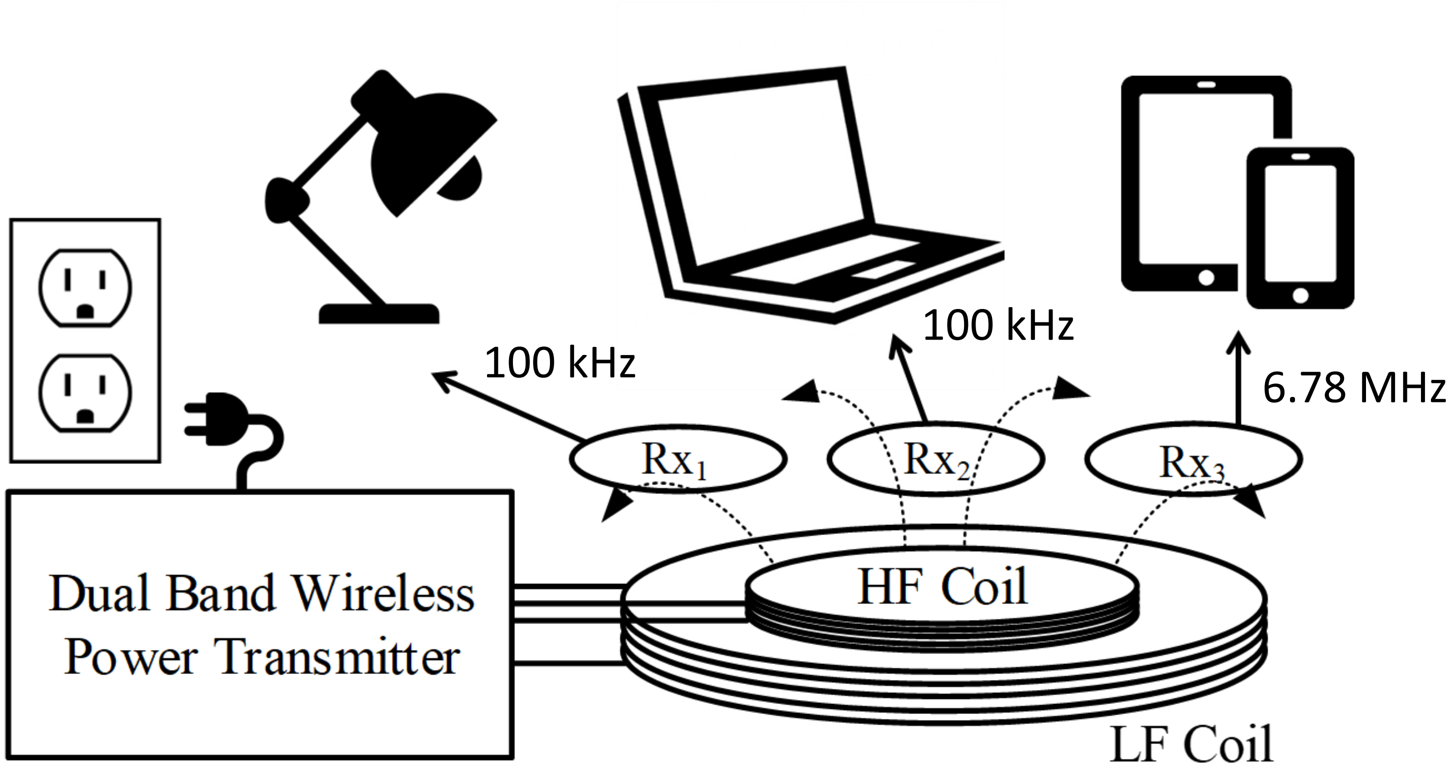
Future Wireless Power Transfer Applications

Dual-Band Multi-Receiver Wireless Power Transfer



kHz wireless power transfer

Higher efficiency
Higher power transfer capability
Large coil size
Low tolerant to misalignment

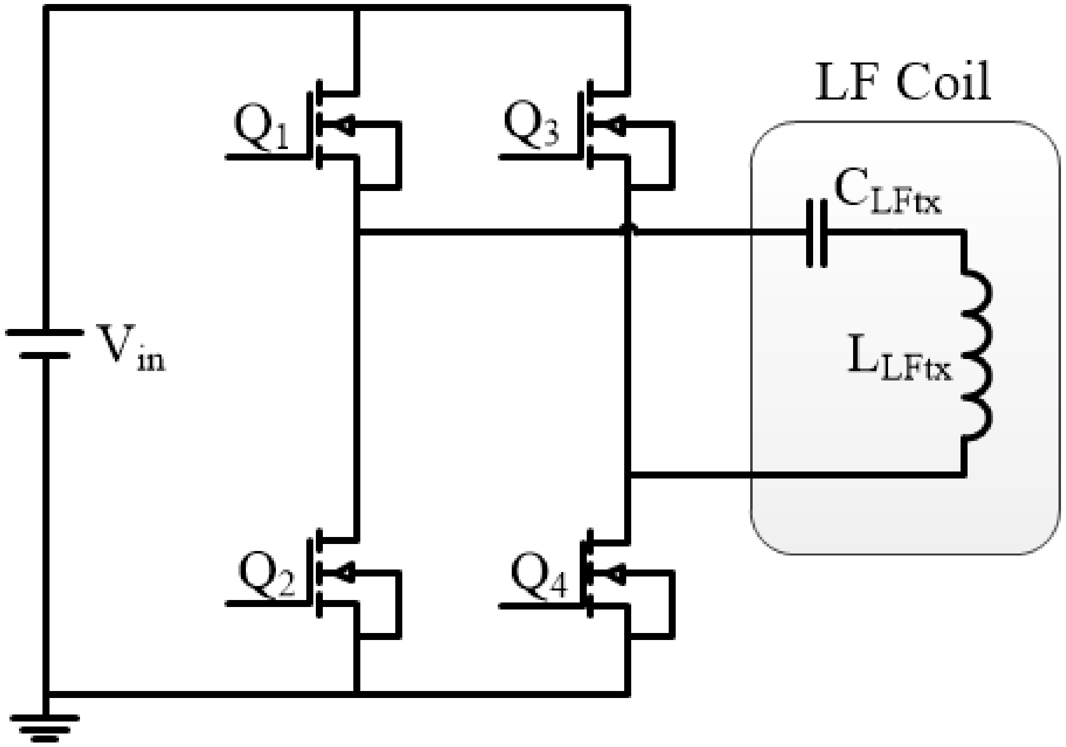
MHz wireless power transfer

Lower efficiency
Lower power transfer capability
Small coil size
High tolerance to misalignment

Support multiple frequency bands; very wide impedance variation range

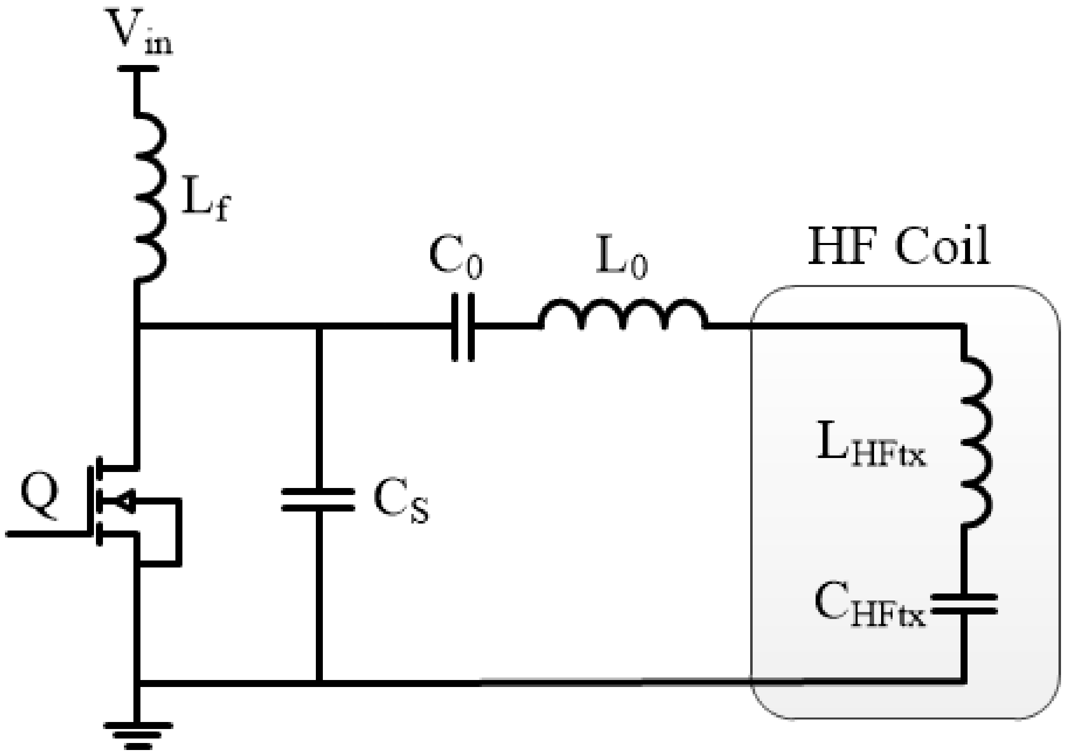
Topology Candidates for Dual-Band WPT

Typical kHz WPT Transmitter



(Full bridge inverter)

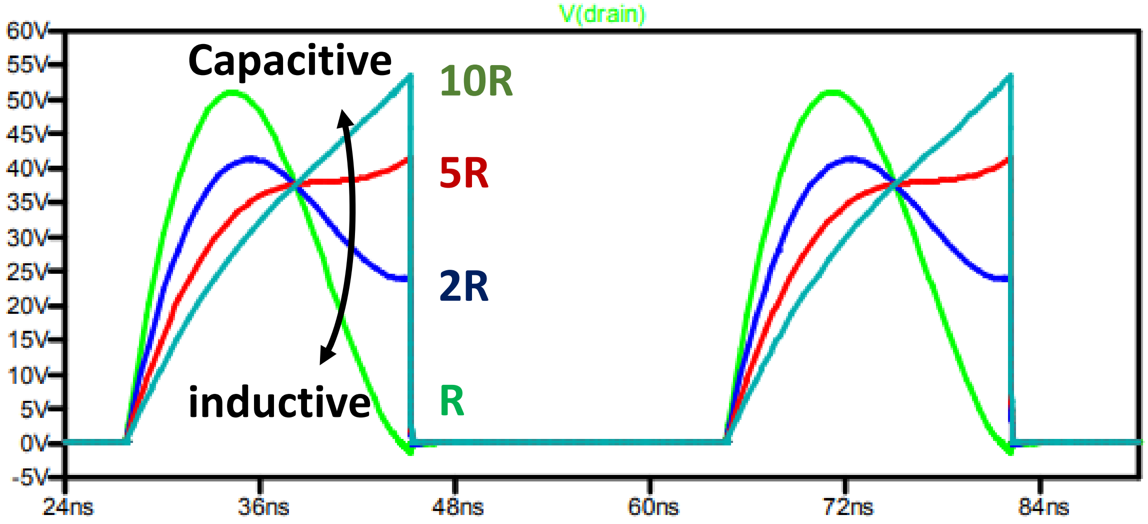
Typical MHz WPT Transmitter



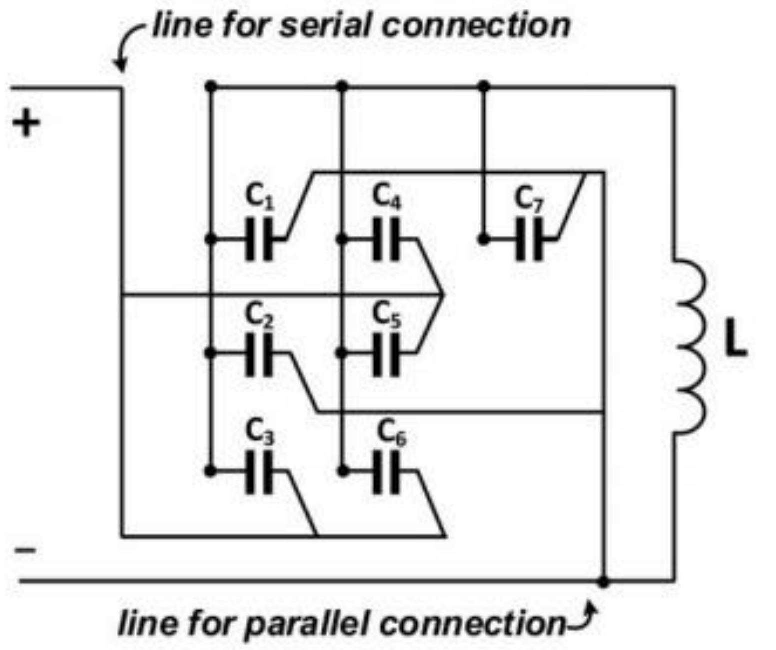
(Class E inverter)

Challenges of HF WPT with Single-Switch PAs

- Co-location of multiple receivers induces large impedance variation
- Class-E PAs are sensitive to load impedance variation (resistive and reactive)



Drain voltage of Class-E PAs with impedance/resistance variation

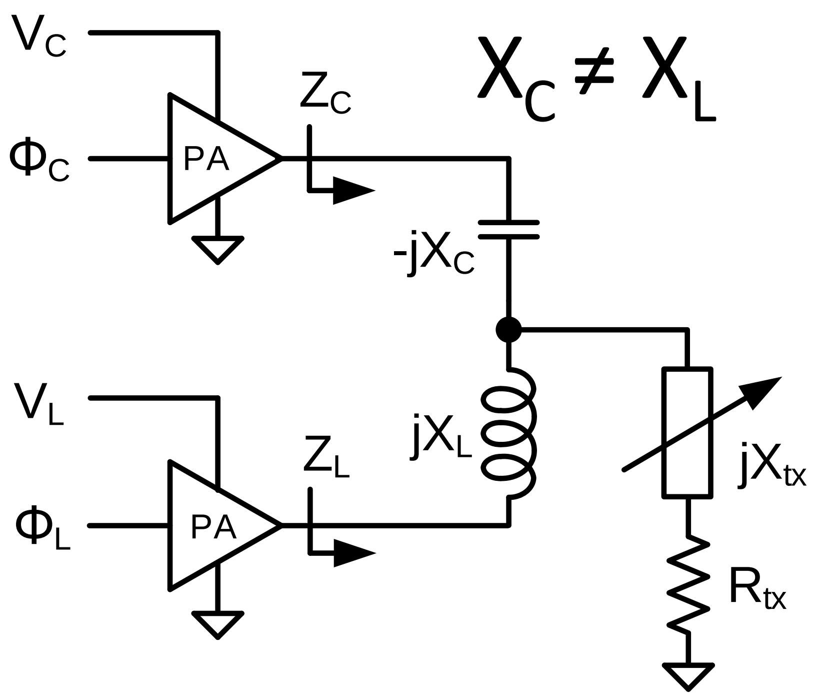


A switched-capacitor tunable matching network

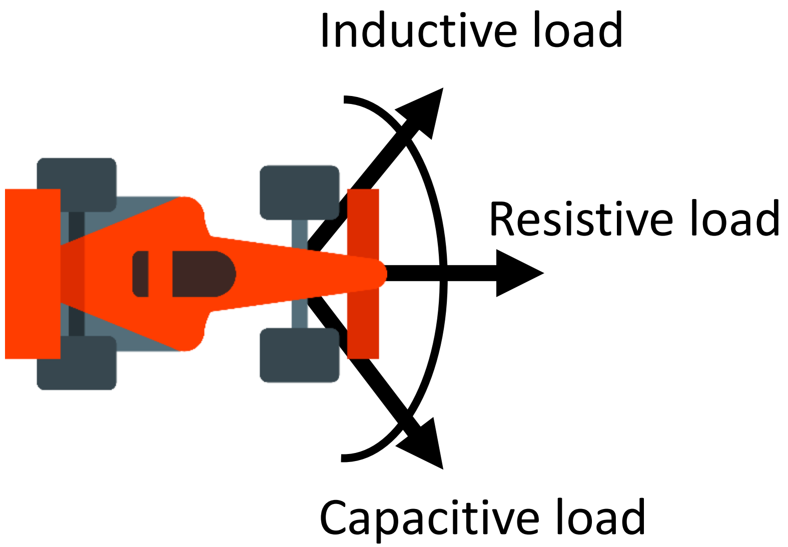
- N. O. Sokal and A. D. Sokal, “Class E-A new class of high-efficiency tuned single-ended switching power amplifiers,” IEEE Journal of Solid-State Circuits, vol. 10, no. 3, pp. 168-176, Jun 1975.
- Y. Lim, H. Tang, S. Lim and J. Park, "An Adaptive Impedance-Matching Network Based on a Novel Capacitor Matrix for Wireless Power Transfer," in *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4403-4413, Aug. 2014.

Principles of the Reactance Steering Network

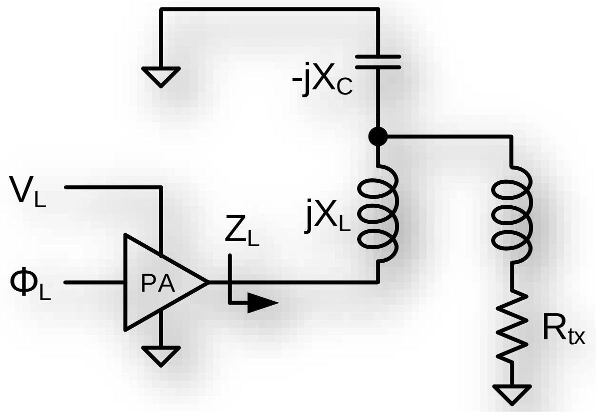
Maintain pure resistive load for both PAs



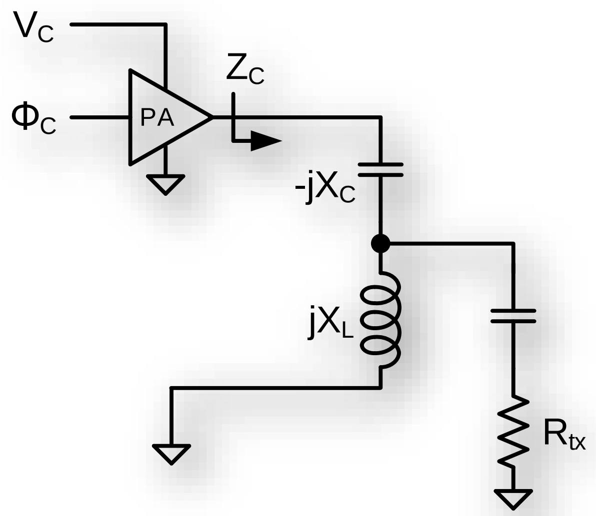
$X_C \neq X_L$



Inductive load



Capacitive load



- **Steering towards capacitive branch with inductive load**
- **Steering towards inductive branch with capacitive load**
- **Compensate for large reactance with small X_L and X_C**

Control of the Reactance Steering Network

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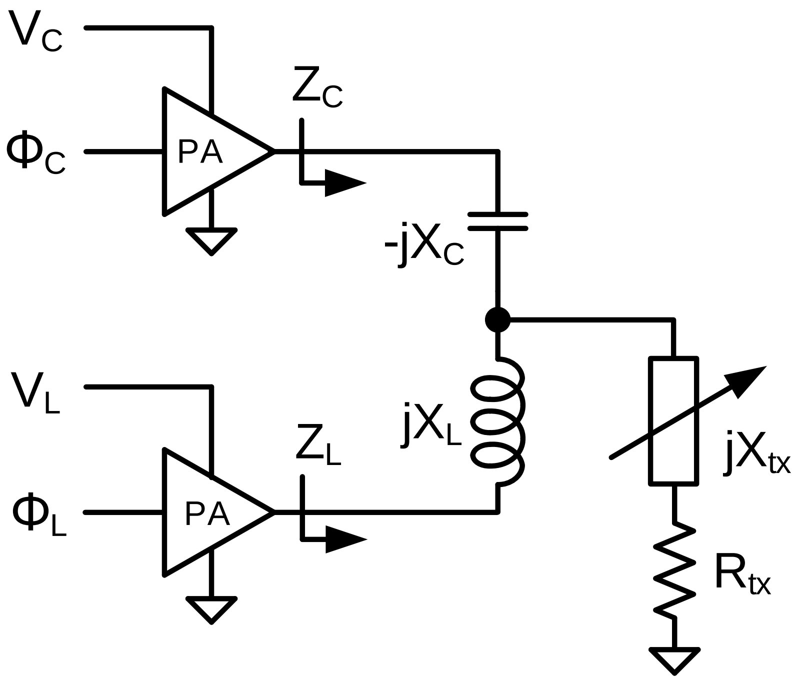
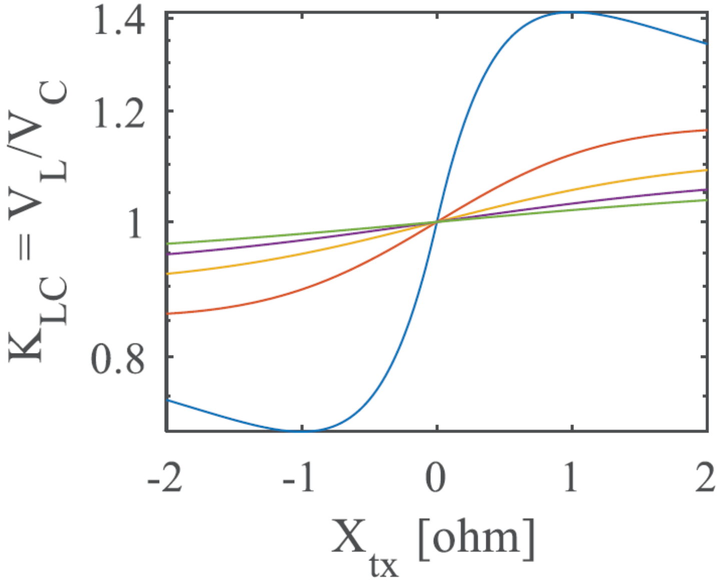
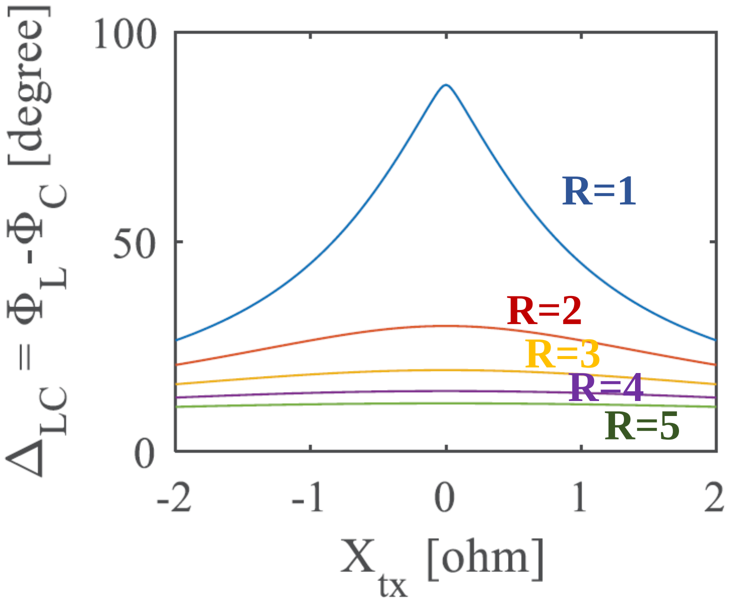


Amplitude Ratio



Phase Difference



Amplitude Ratio

$$K_{LC} = \left|\frac{V_L}{V_C}\right| = \frac{X_O + X_{tx}}{X_{tx}\cos\left(\Delta_{LC}\right) + R_{tx}\sin\left(\Delta_{LC}\right)}$$

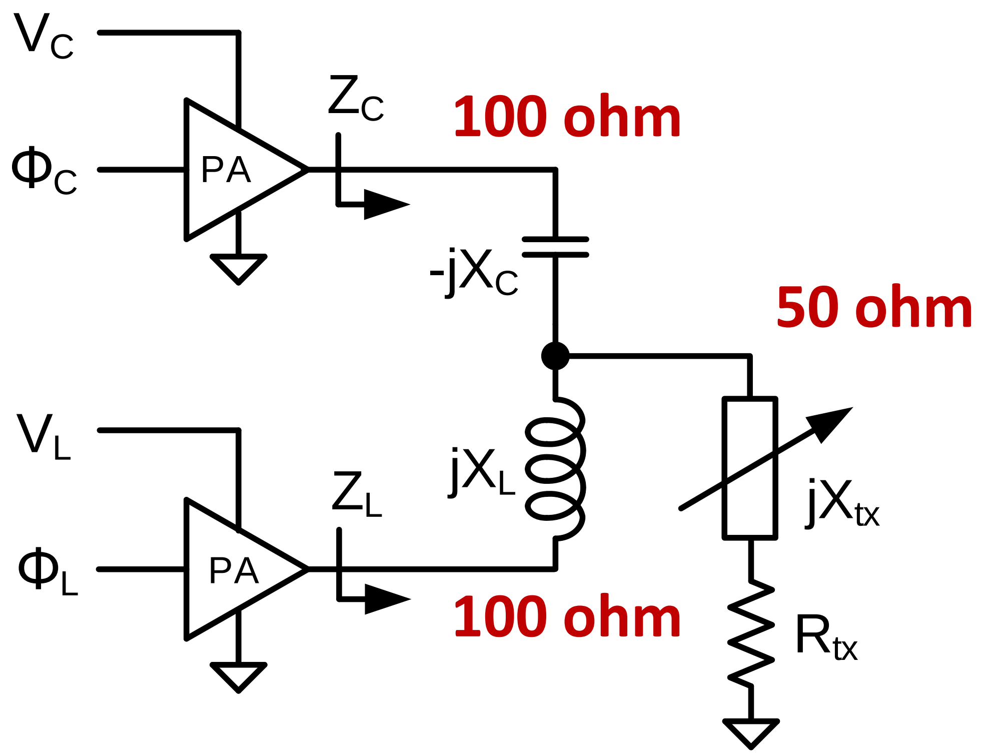
$$\frac{1}{\sqrt{2}} < K_{LC} < \sqrt{2}$$

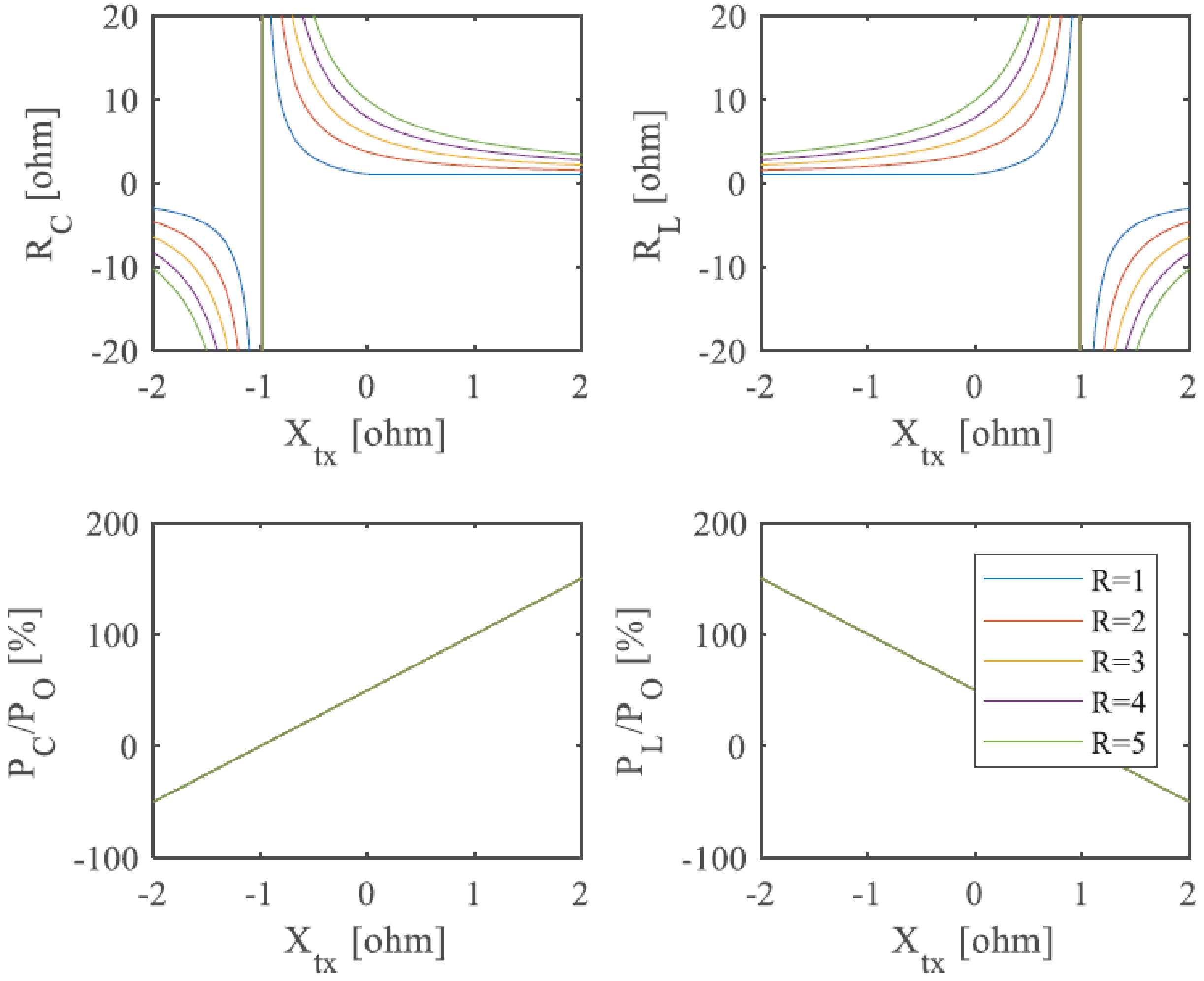
Phase Difference

$$\Delta_{LC} = \Phi_L - \Phi_C = \arcsin\sqrt{\frac{X_O^2}{X_{tx}^2 + R_{tx}^2}}$$

$$0^\circ < \Delta_{LC} < 90^\circ$$

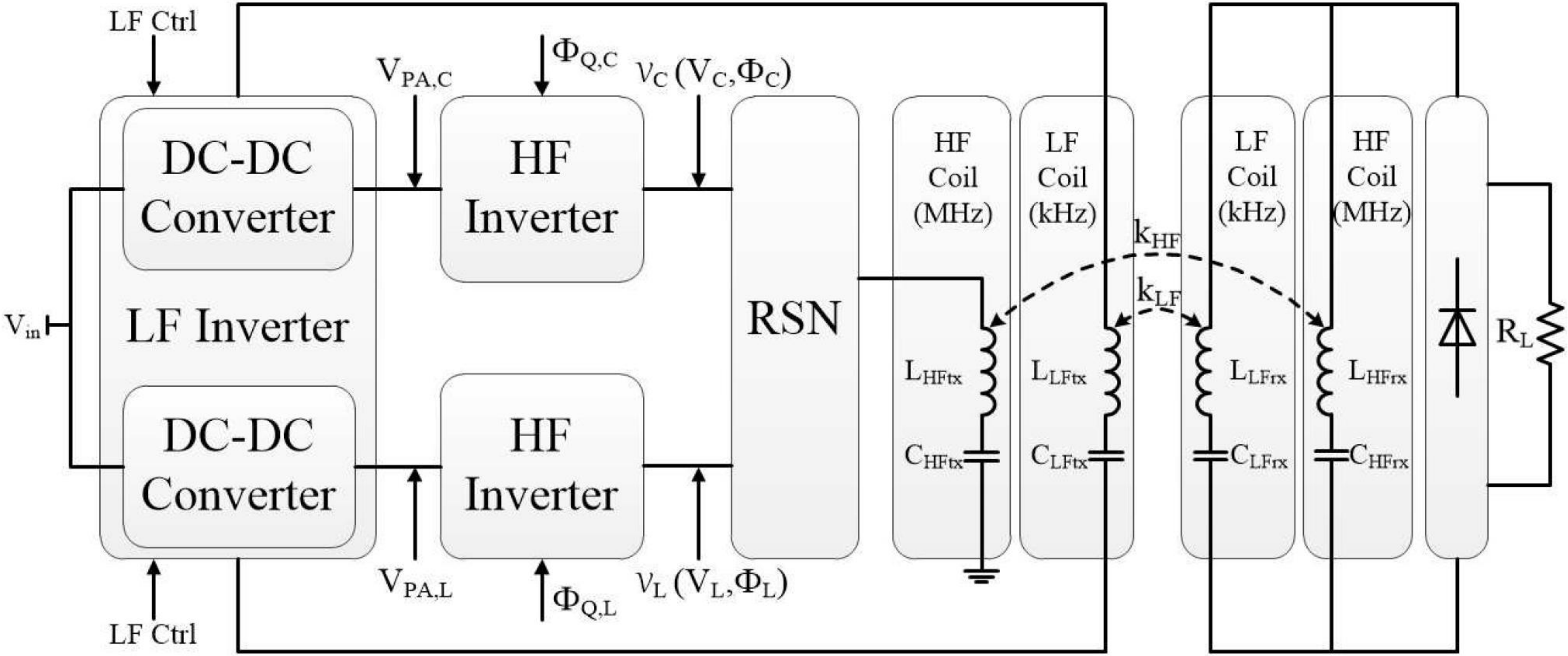
Load Resistance and Adaptive Power Sharing





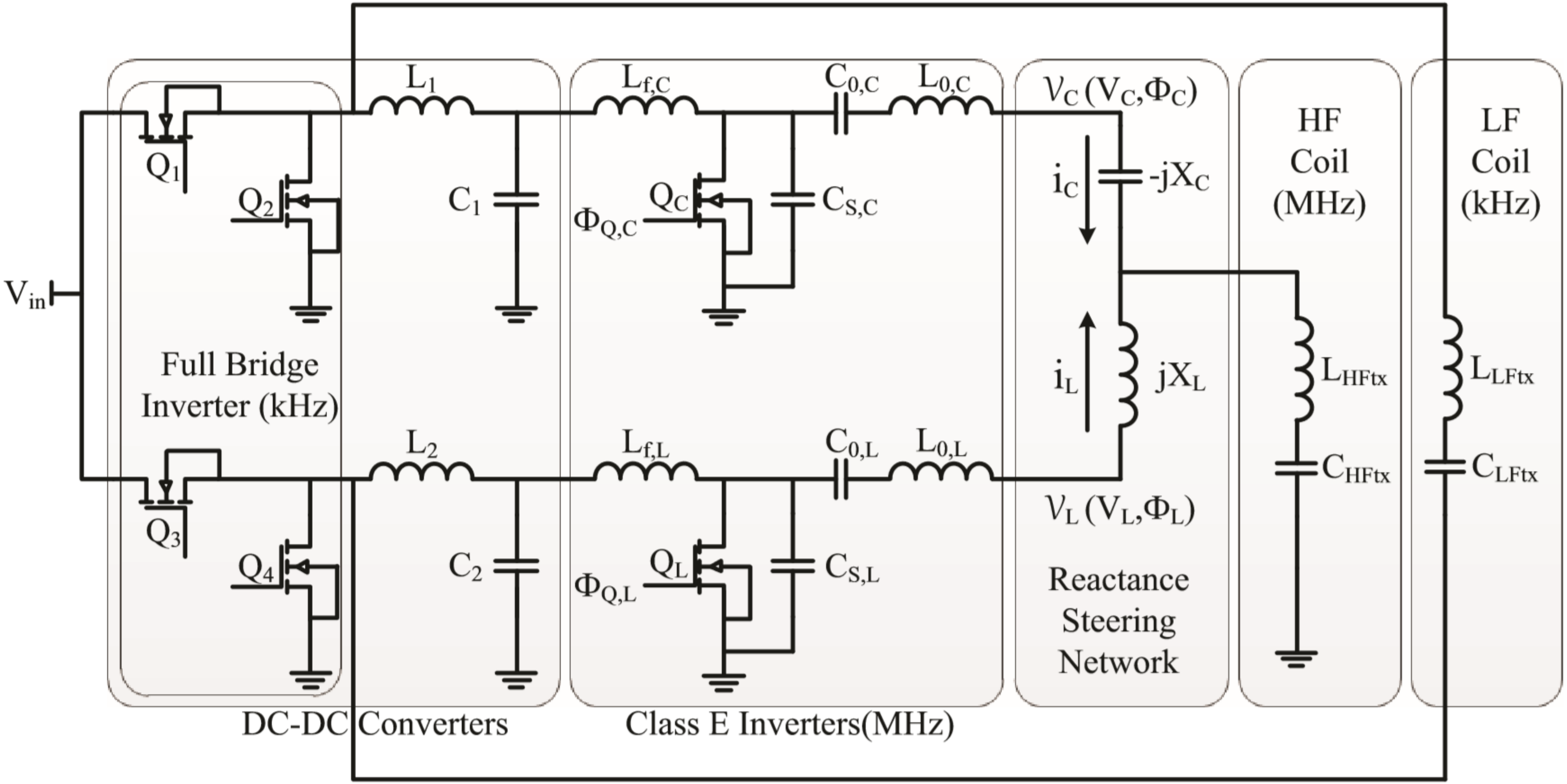
- **Both PAs always see pure resistive load**
- **Both PAs adaptively split the power**
- **When reactance is very high, one PA functions as a rectifier with negative resistance**

Dual-Band Multi-Receiver WPT Architecture with RSN



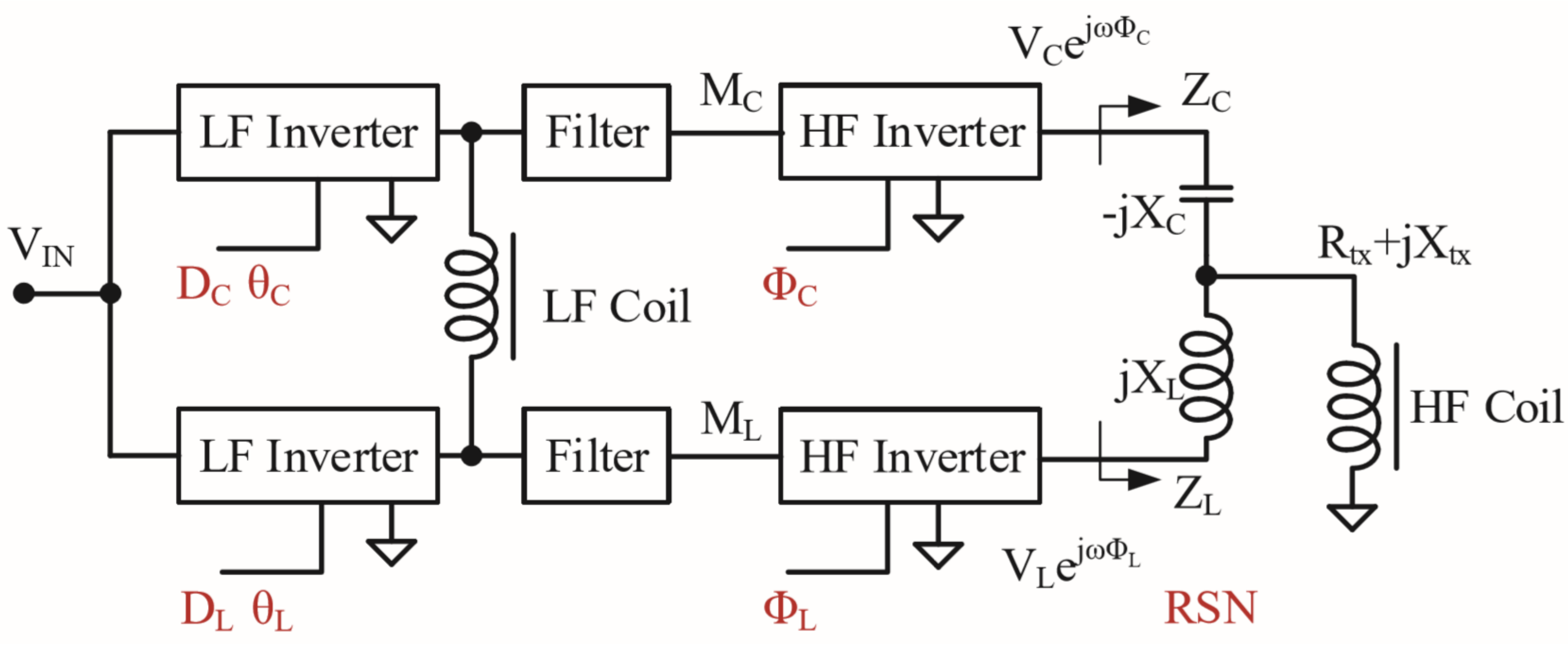
Merge LF and HF Transmitters, and create mutual advantages

Low Component Count Dual Band Transmitter



The dc-dc converters can be implemented as a part of front-end PFC

Decoupled Control of the HF and LF Operation

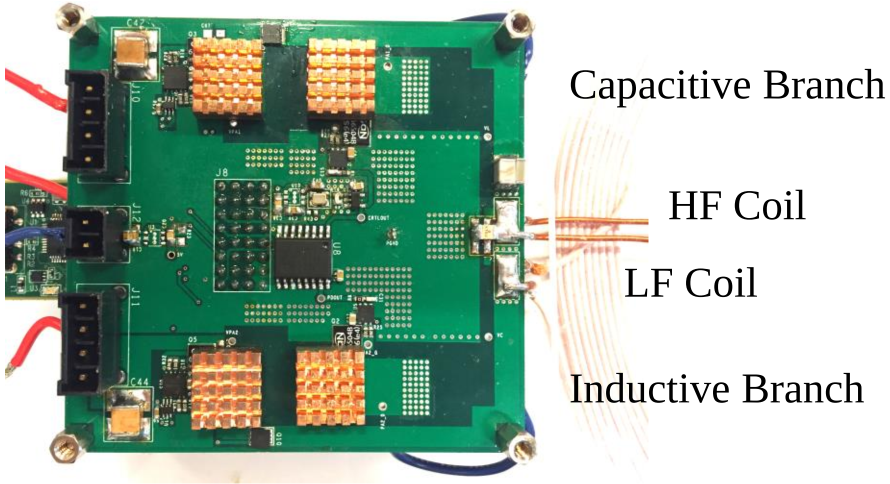


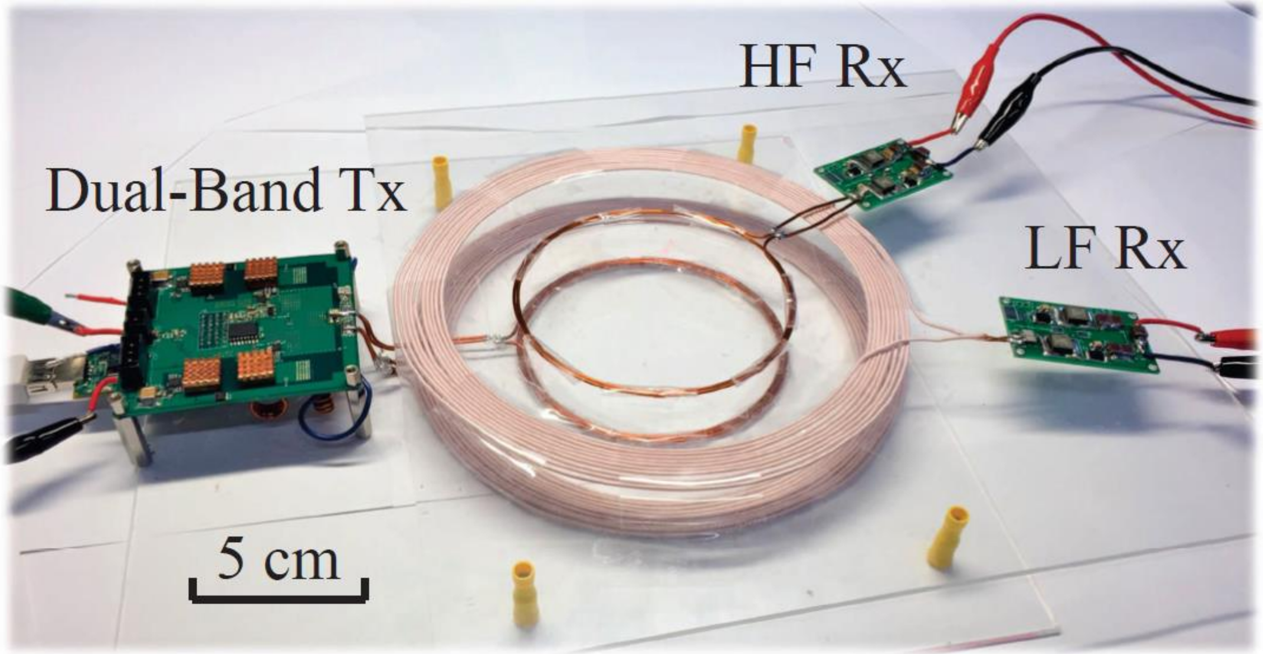
Control variables for the HF coil: D_C, D_L, Φ_C, Φ_L

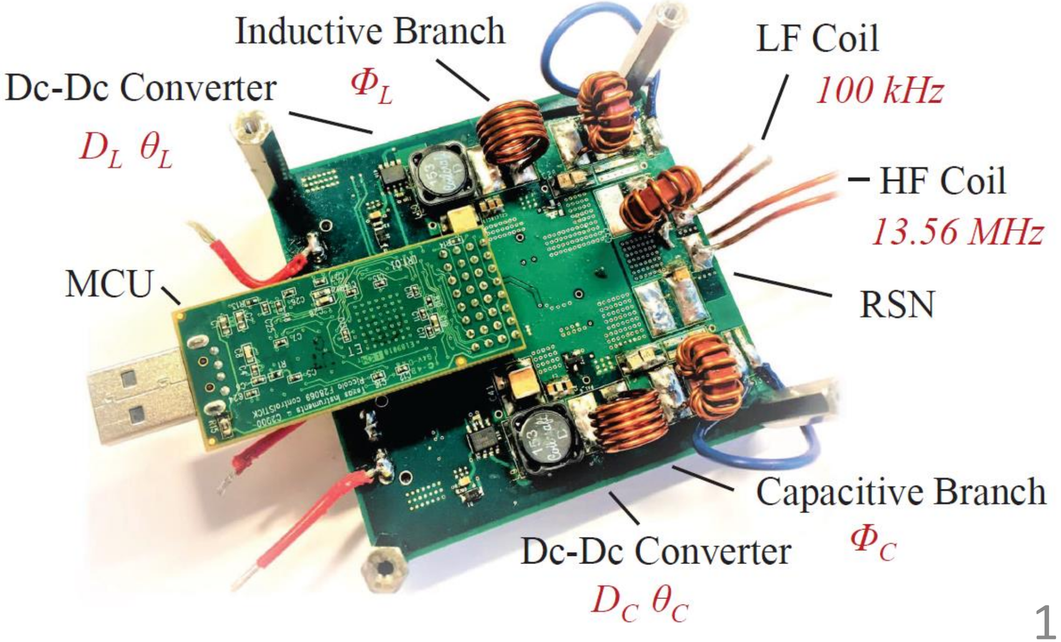
Control variables for the LF coil: $D_C, D_L, \theta_C, \theta_L$

A Dual-Band Multi-Receiver WPT Prototype

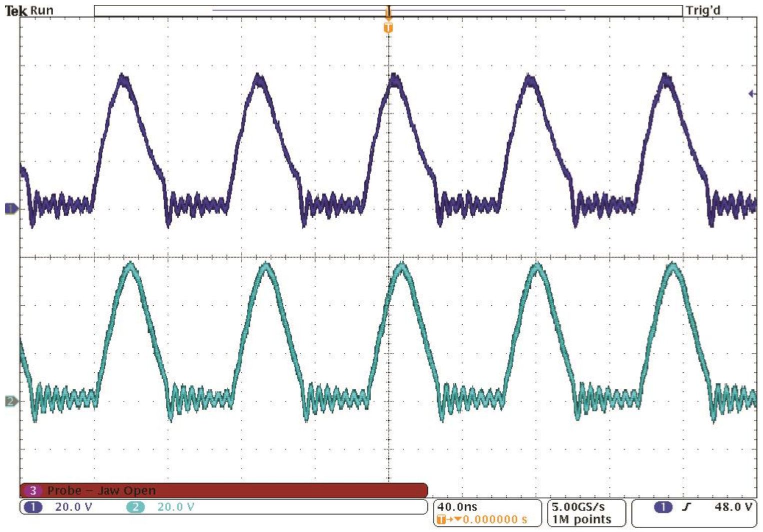
Dual Band Operation: 100 kHz and 13.56 MHz
Power Rating: 65 W@100 kHz, 65 W@13.56 MHz
Input Voltage: 50 V (up to 80 V)
Output Voltage: 30 V@100 kHz, 30 V@13.56 MHz
Spacing: 2.8 cm distance, up to 3 cm misalignments
Coil size: Coil_HF (D=10 cm), Coil_LF (D=20 cm)



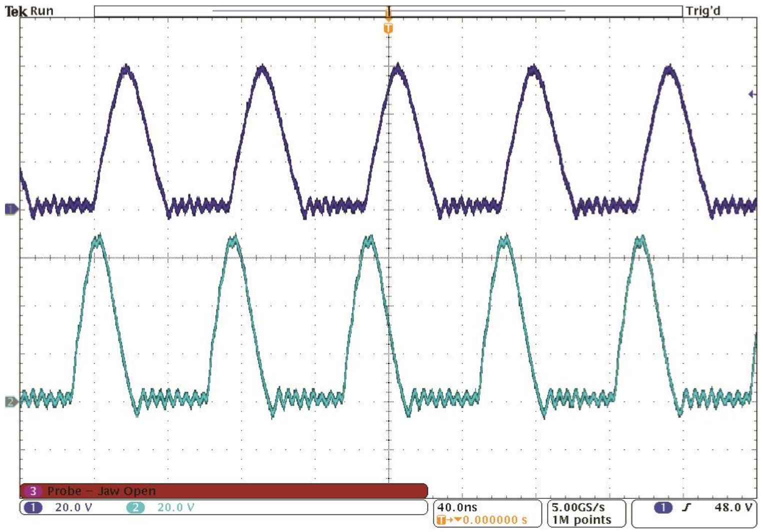




ZVS of Both Class-E PAs across Very Wide Reactance Range

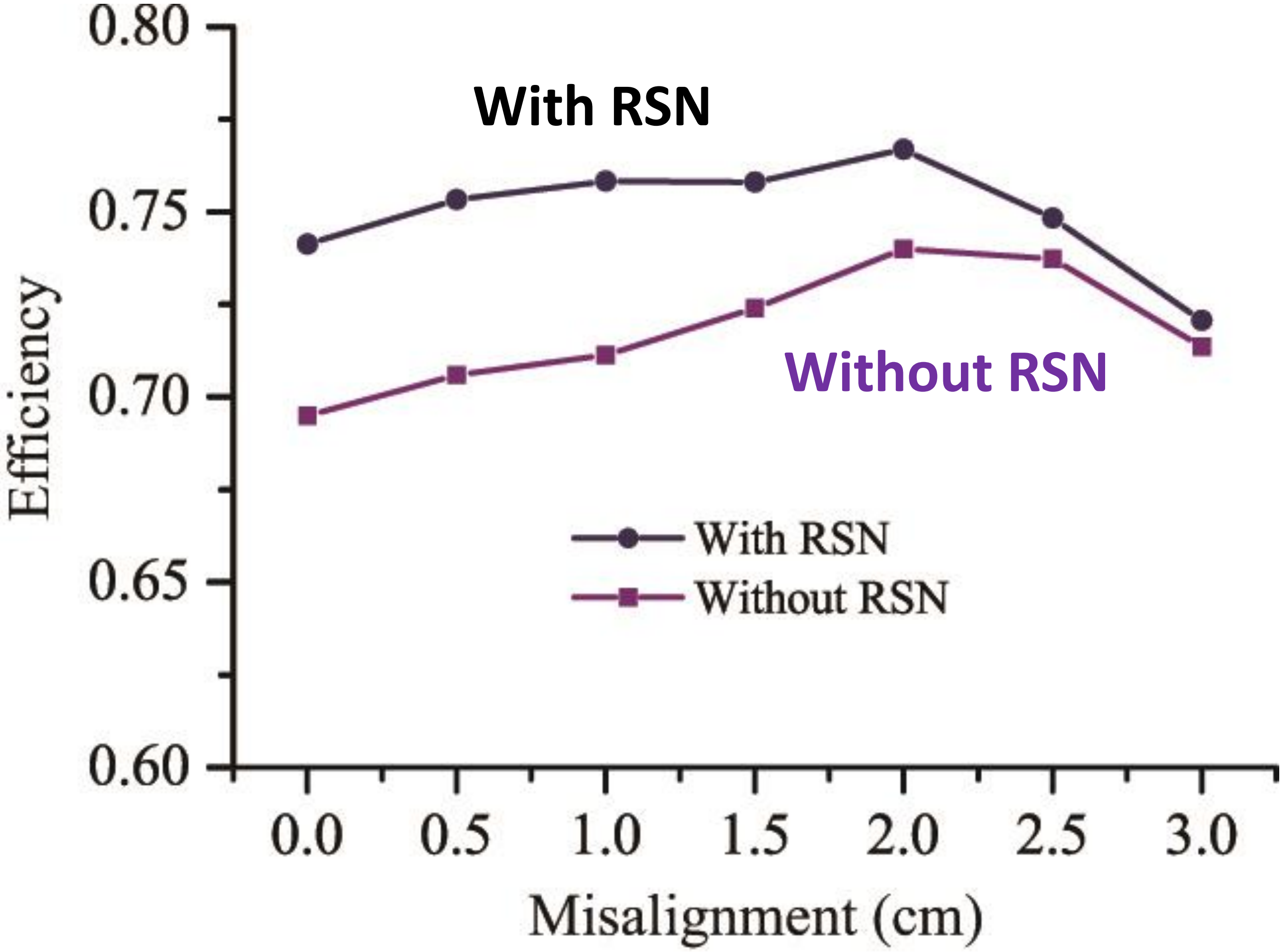


Example drain voltage without RSN



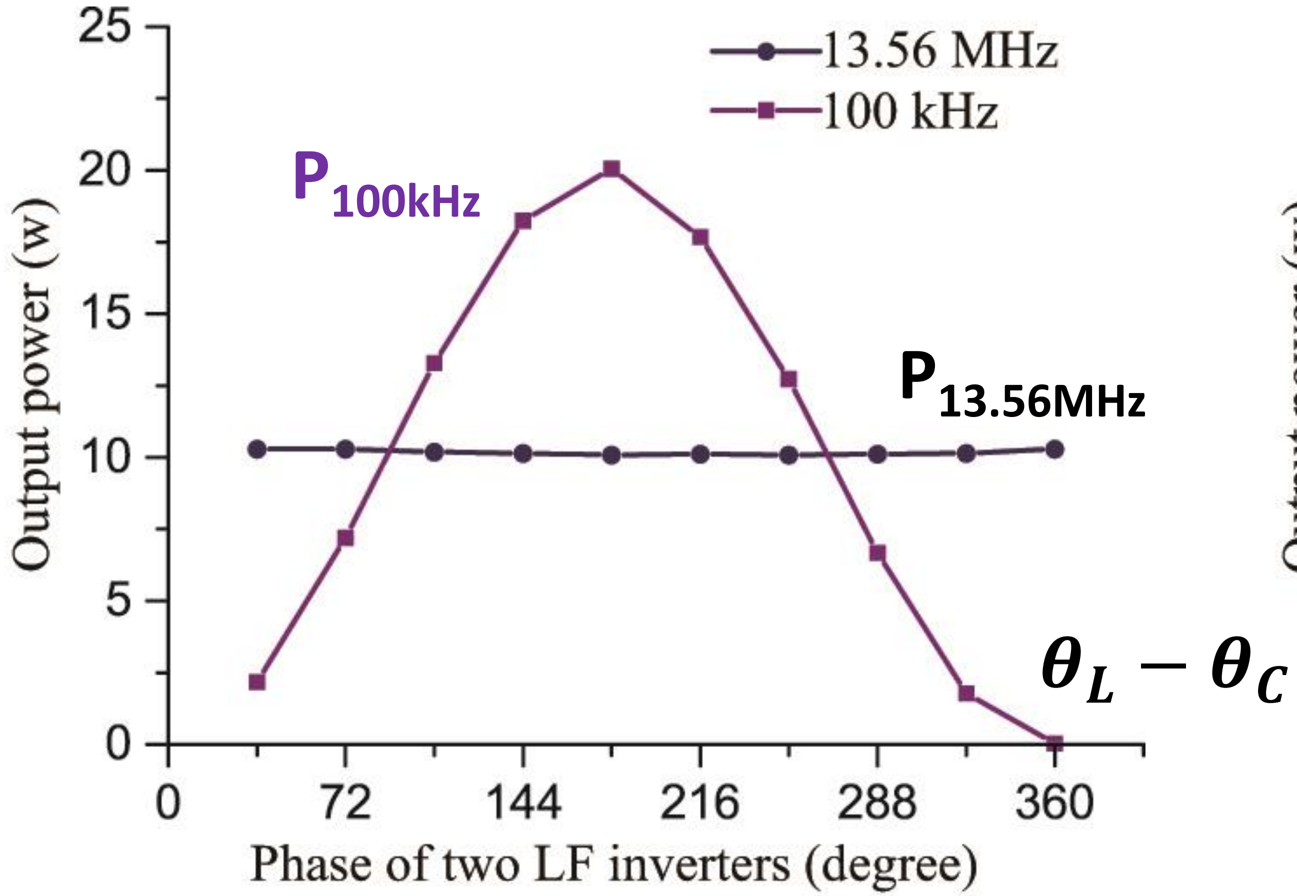
Example drain voltage with RSN

- Efficiency vs. misalignment (0 ~ 3 cm)
- Fixed output power 30W
- Reactance range from 0j Ω to 80j Ω

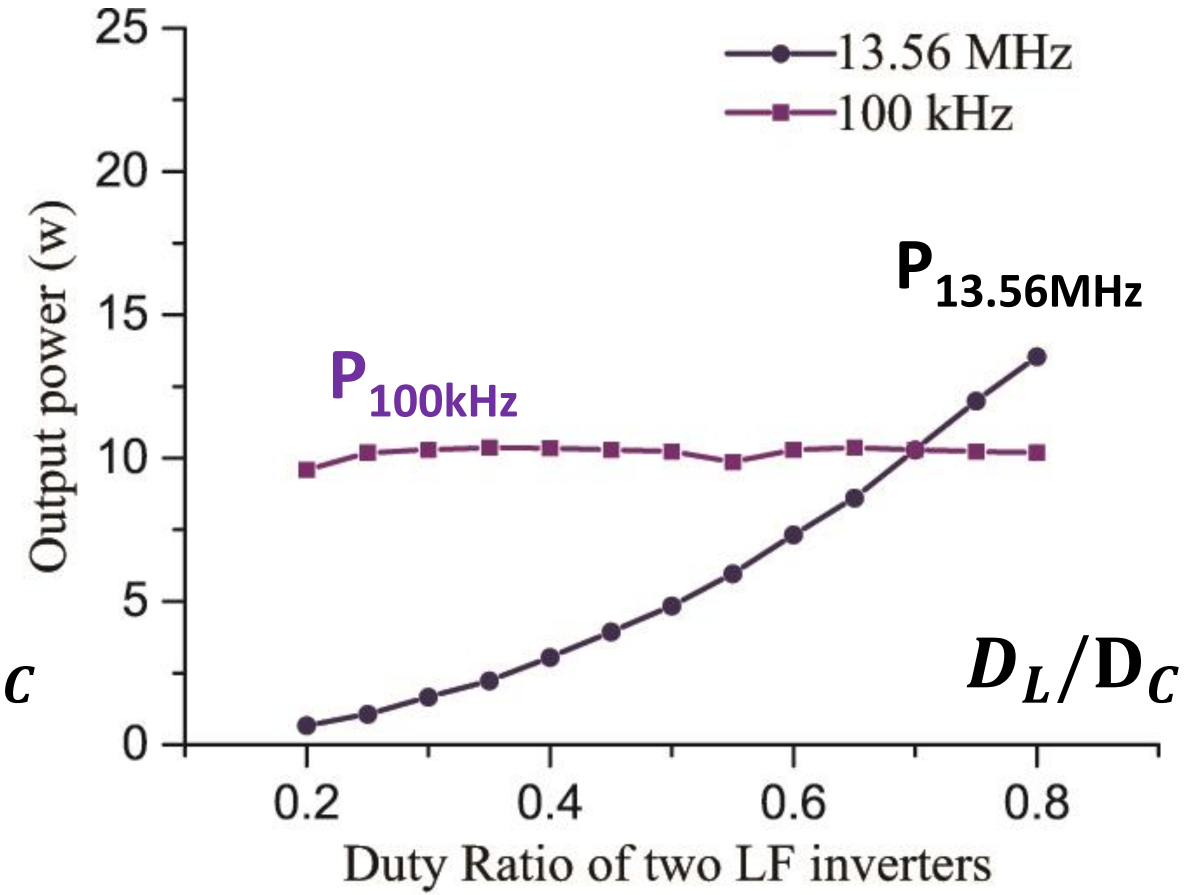


Decoupled Modulation of the Two Bands

- Modulating power at 100 kHz
- Maintaining 10 W at 13.56 MHz



- Modulating power at 13.56 MHz
- Maintaining 10 W at 100 kHz



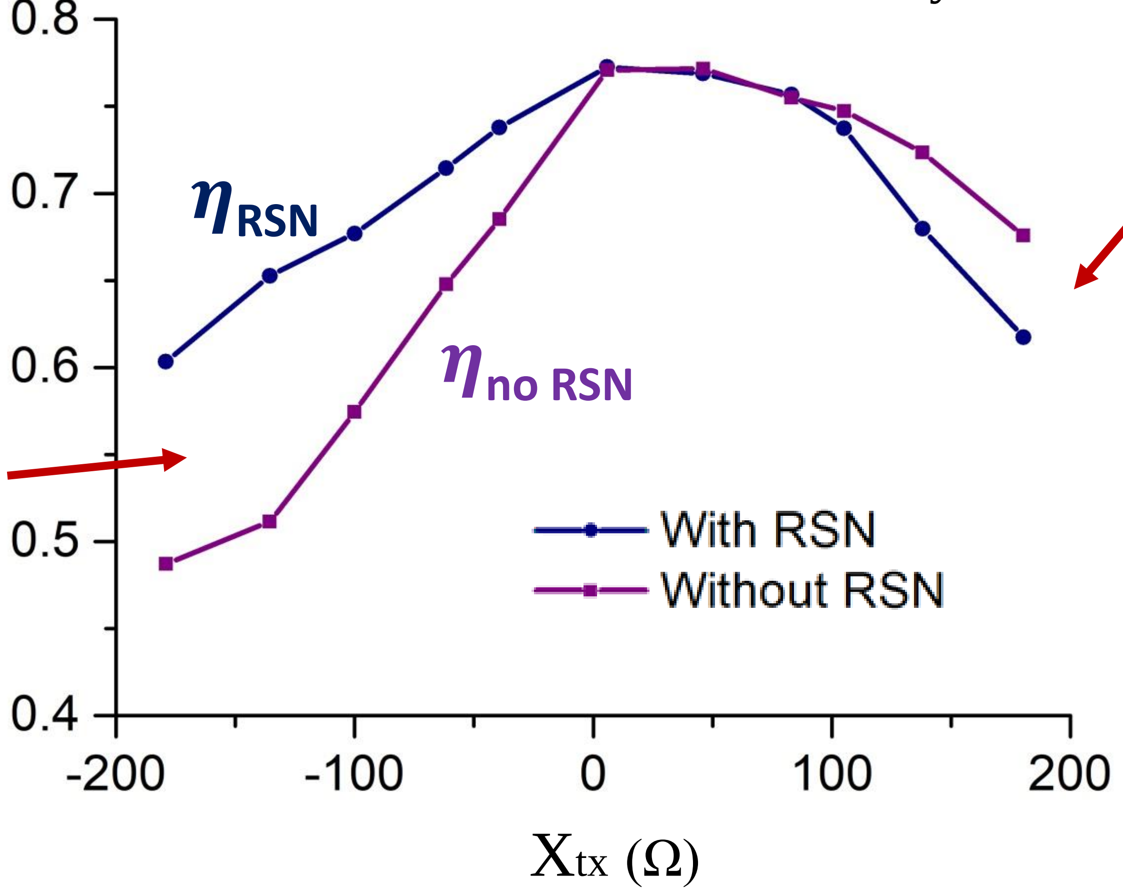
HF WPT Efficiency with “Very” Reactive Load

- RSN significantly improves the HF WPT efficiency with capacitive X_{tx}.
- RSN sacrifices more loss with very inductive load (due to circulating current).

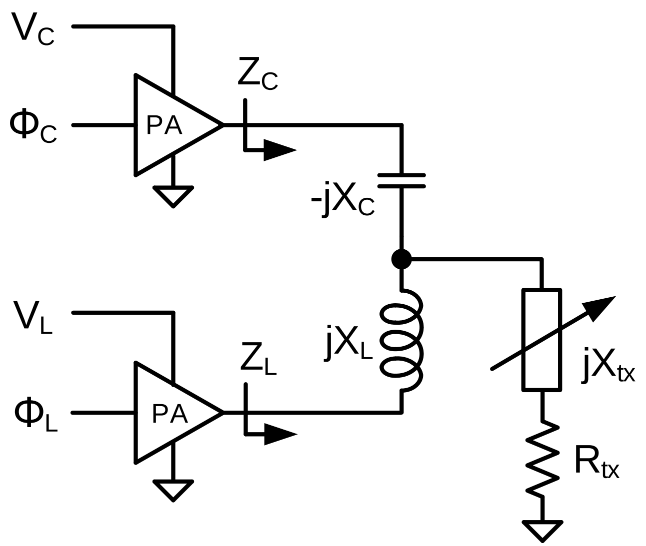
R: 50 Ω
X: -200 Ω to +200 Ω

12% higher efficiency with “very” capacitive load

13.56 MHz End-to-End Efficiency



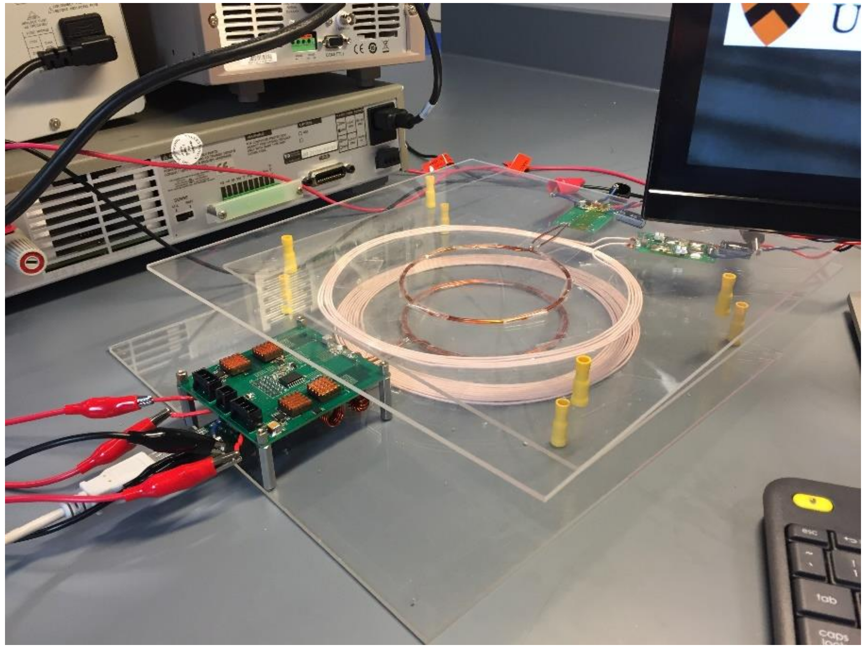
4% lower efficiency with “very” inductive load

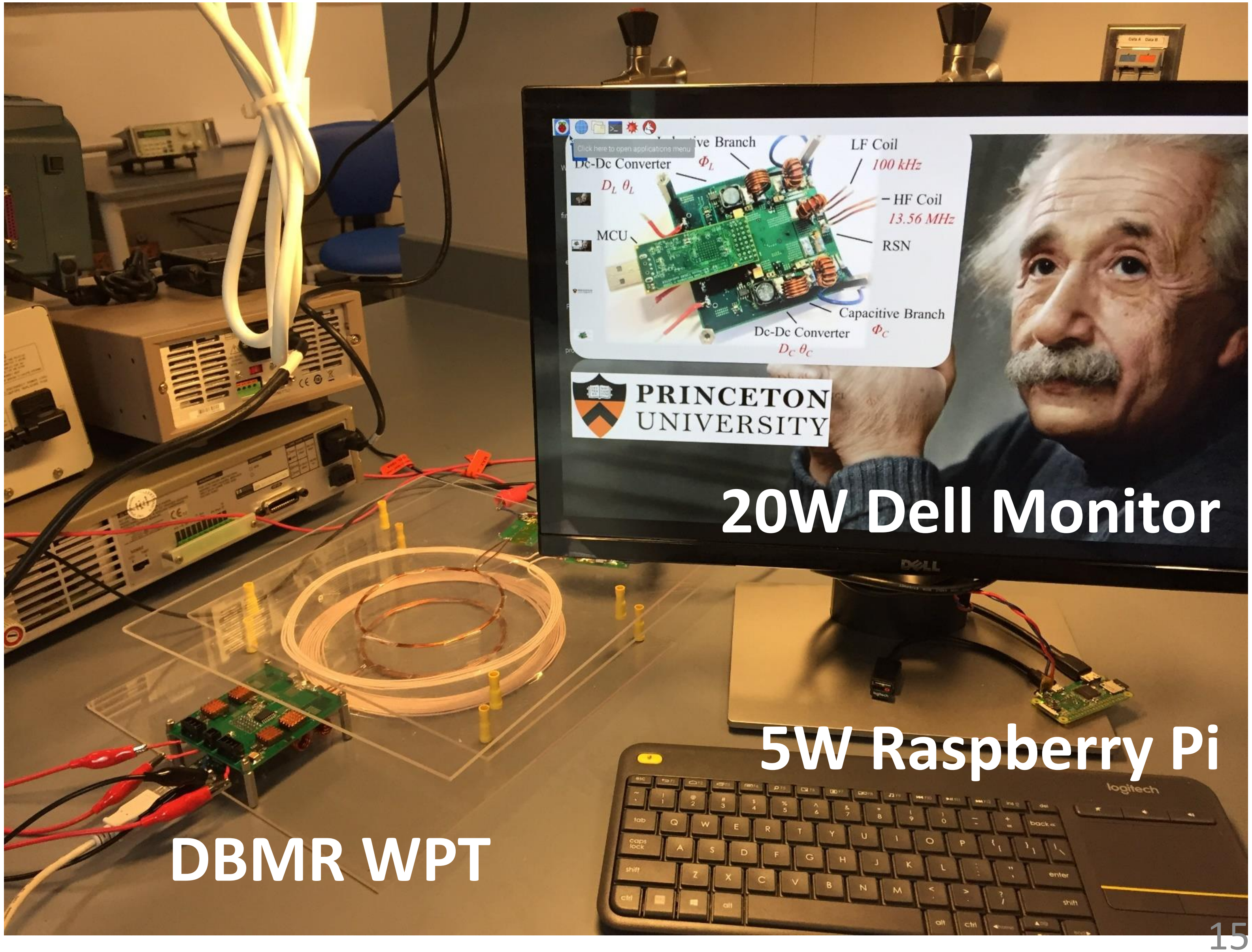


Demo: A Dual-band Wireless Powered Desktop System

Demo: a dual-band wireless powered desktop computer

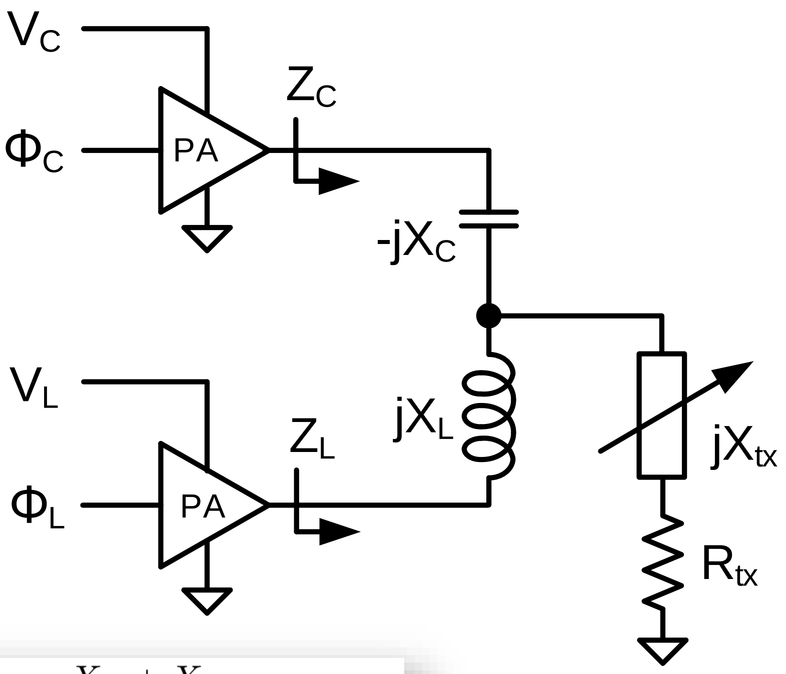
Dell Monitor: 20W @ 100 kHz
Raspberry Pi: 5W @ 13.56 MHz
Efficiency: ~ 75%, end to end

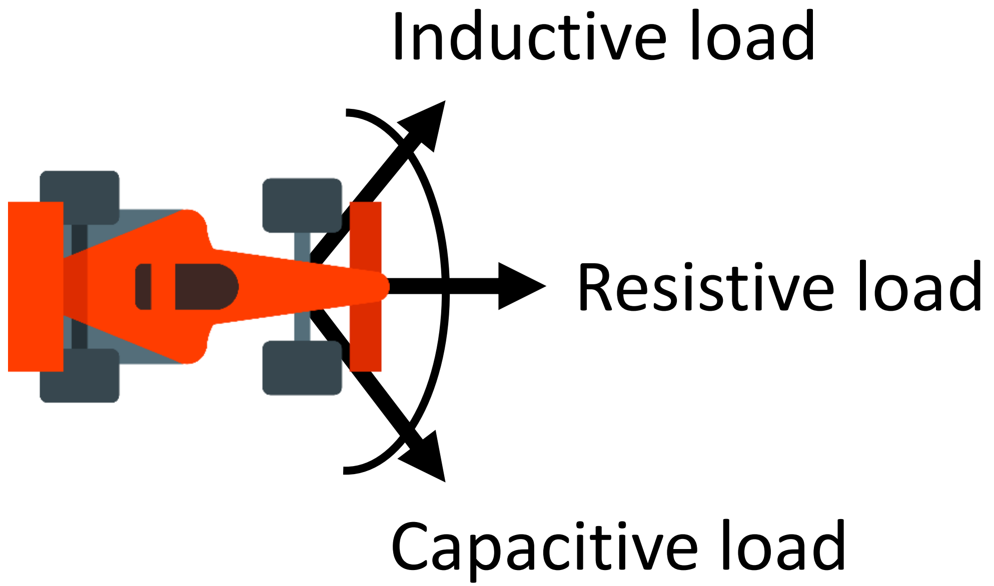


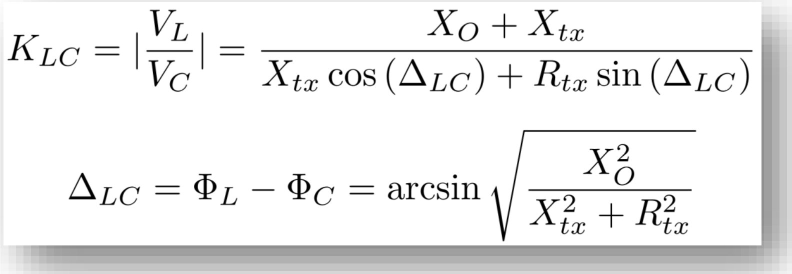


Summary

- Theory: Reactance Steering Network (RSN) for RFPAs.
- Application: HF/VHF power conversion with load impedance variation.
- Example: A dual-band multi-receiver wireless power transfer system.







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$$\Delta_{LC} = \Phi_L - \Phi_C = \arcsin\sqrt{\frac{X_O^2}{X_{tx}^2 + R_{tx}^2}}$$

Fully active load impedance compensation