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Coil Design for Wireless Power Transfer

Daniel Costinett

With contributions from

Ruiyang Qin, Jie Li

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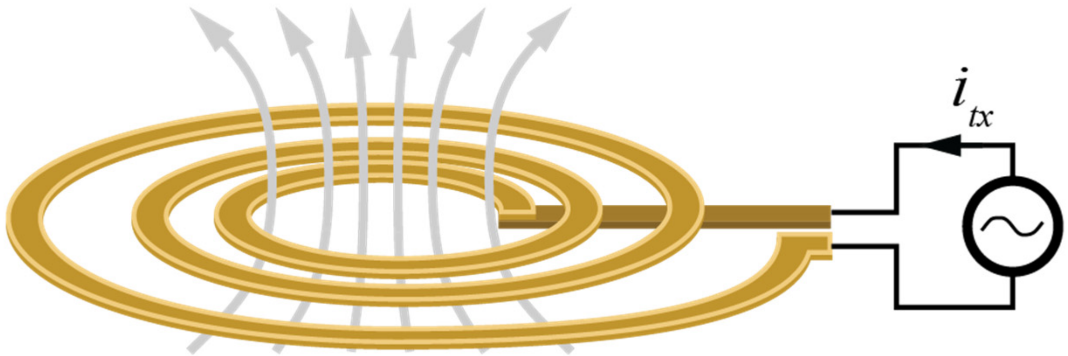
Wireless Power Transfer (WPT)



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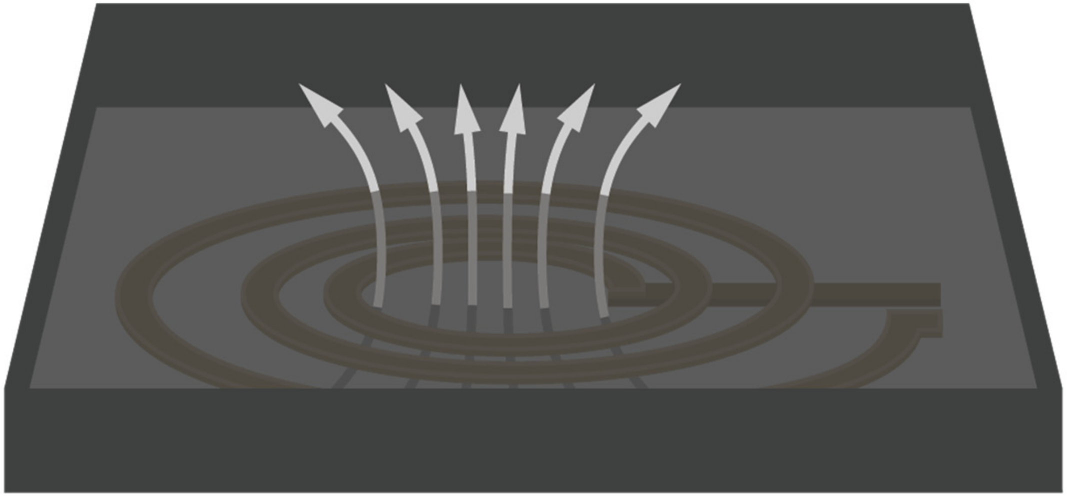

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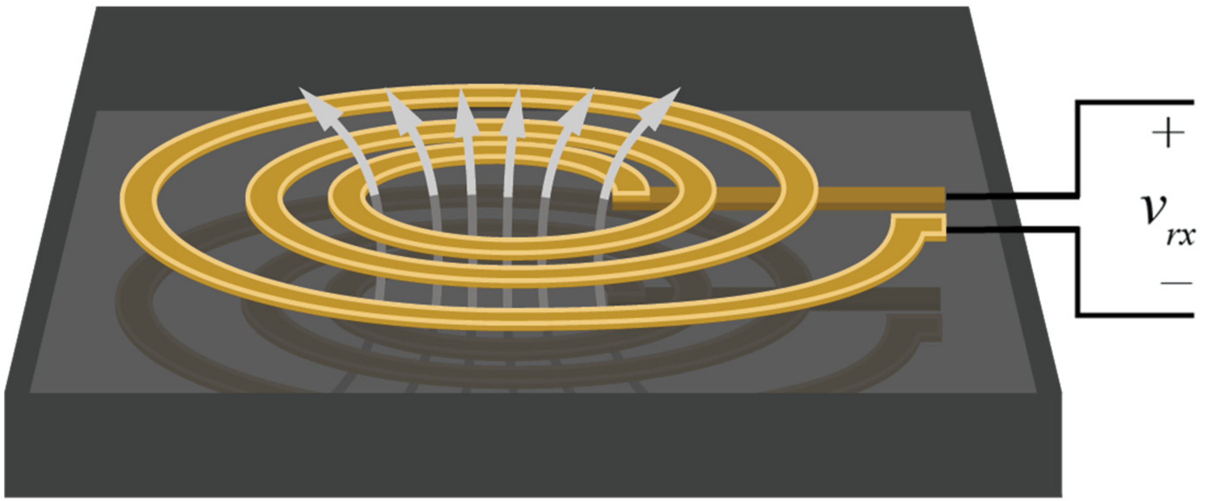

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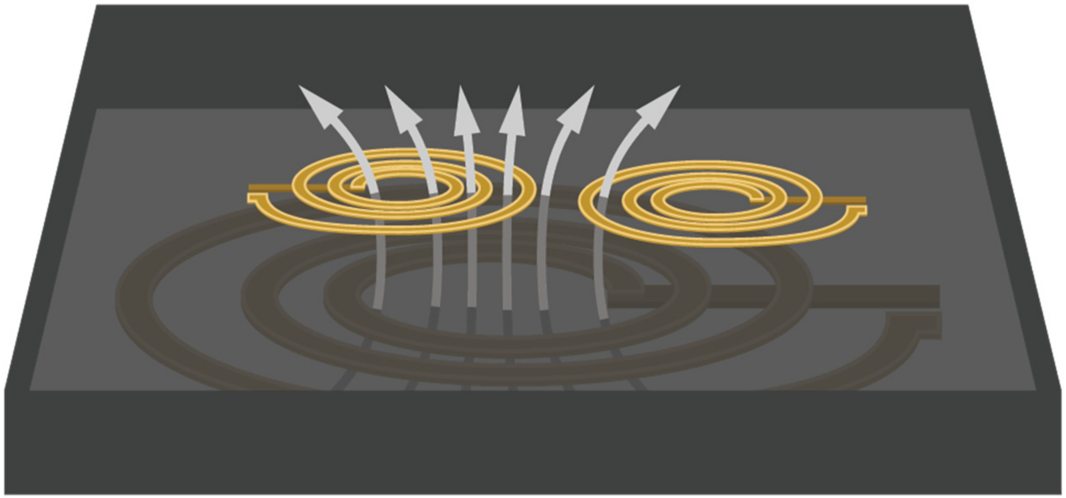

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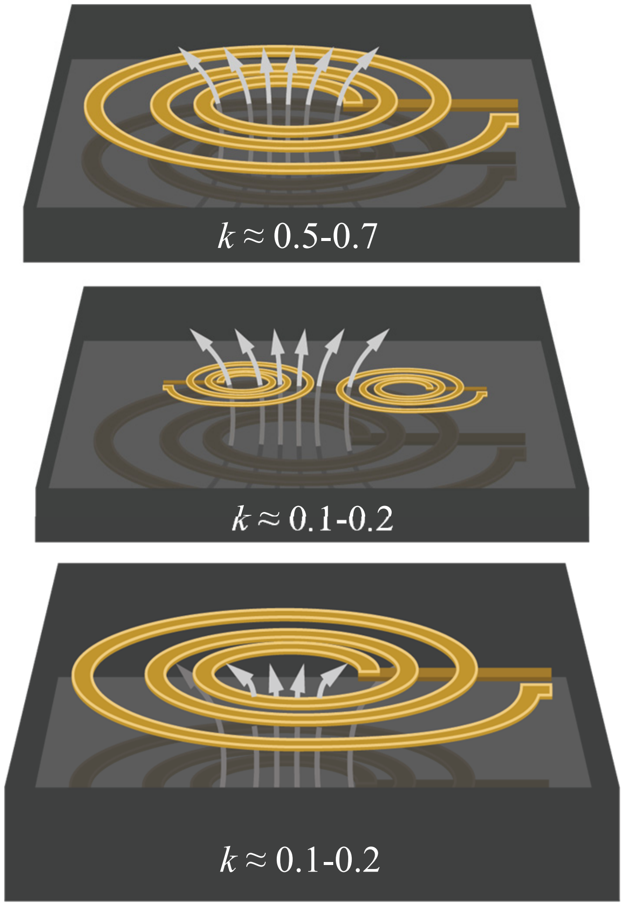
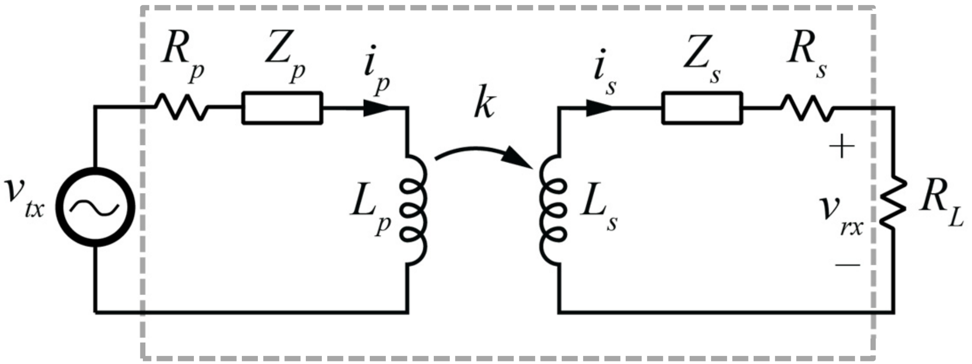
Modeling Inductive Links

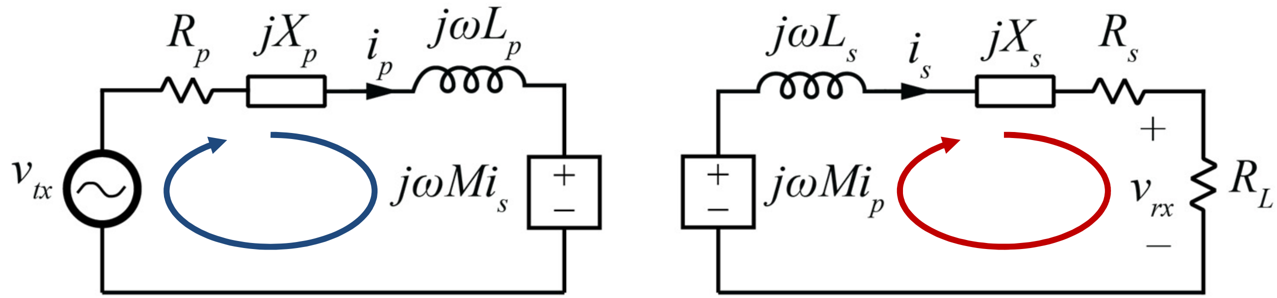




$$k = \frac{M}{\sqrt{L_p L_s}}$$

- To limit EMI & ac coil losses, i_p and i_s should be dominantly single-frequency (ω)
- Z_p and Z_s represent any additional reactance added or generated from Tx/Rx implementation

Modeling Inductive Links



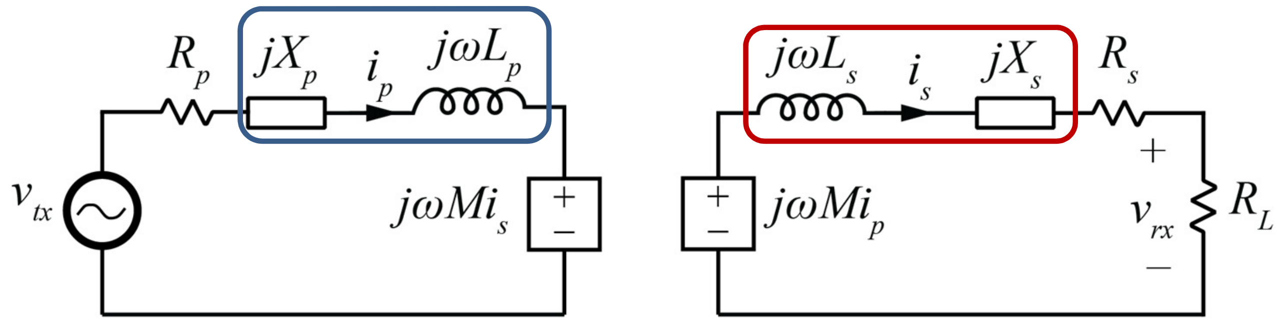
$$v_{tx} = i_p\left(j\omega L_p + jX_p + R_p\right) + i_s(j\omega M)$$

$$v_{rx} = i_s R_L = -i_s(j\omega L_s + jX_s + R_s) + i_p(j\omega M)$$

- With resistive load, average $P_{out} = ½|i_s|^2 R_L$
- The secondary current i_s results from the biasing source $j\omega M i_p$, where

$$\frac{i_p}{i_s} = \frac{R_L + j\omega L_s + jX_s + R_s}{j\omega M}$$

Modeling Inductive Links



$$v_{tx} = i_p\left(\boxed{j\omega L_p + jX_p} + R_p\right) + i_s(j\omega M)$$

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- Any net reactance on the secondary will increase primary current at the same power, increasing losses on R_p
- Any net reactance on the primary will not affect loss, but will require increased amplitude of v_{tx}

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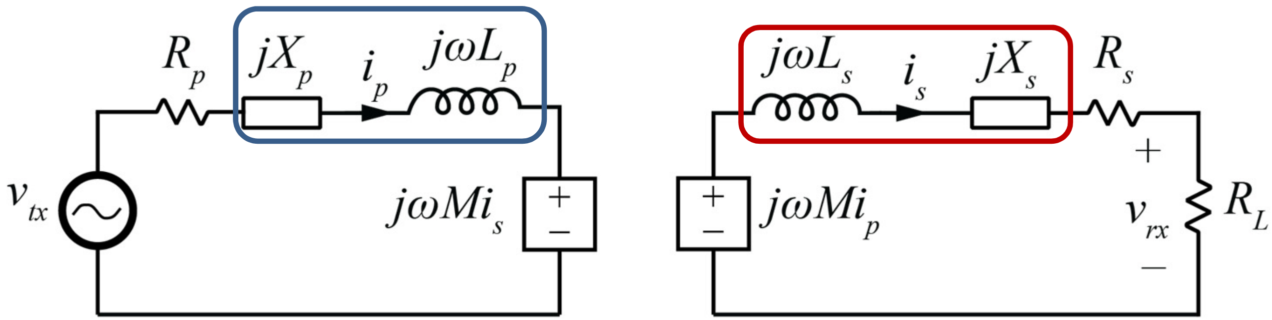
Modeling Inductive Links



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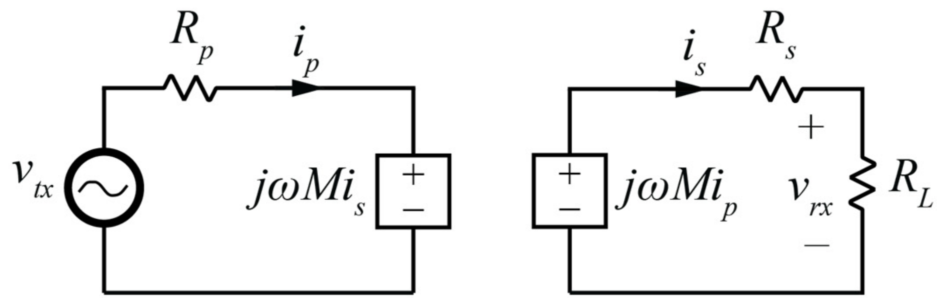
- Any net reactance on the secondary will increase primary current at the same power, increasing losses on R_p
- Any net reactance on the primary will not affect loss
  - Set $X_i = -\omega L_i$
  - Control, unloaded, short circuit operation require additional consideration

Modeling Inductive Links



$$v_{tx} = i_p(R_p) + i_s(j\omega M\ )$$

$$v_{rx} = i_s R_L = -i_s(R_s) + i_p(j\omega M\ )$$

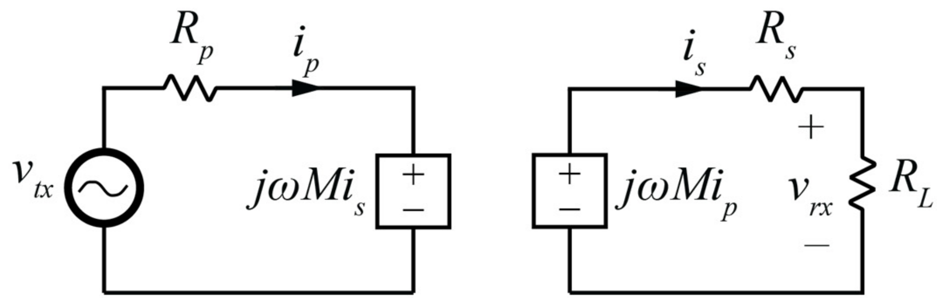
With series-resonance of both coils at ω

$$\frac{i_p}{i_s} = \frac{R_L + R_s}{j\omega M}$$

The power transfer efficiency is

$$\eta = \frac{\frac{1}{2}|i_s|^2 R_L}{\frac{1}{2}|i_s|^2 R_L + \left(\frac{1}{2}|i_s|^2 R_s + \frac{1}{2}\left|i_p\right|^2 R_p\right)} = \frac{1}{1 + \frac{R_s}{R_L} + \frac{\left|i_p\right|^2}{|i_s|^2}\frac{R_p}{R_L}} = \frac{1}{1 + \frac{R_p(R_L + R_s)}{\omega^2 M^2}}\left(\frac{R_L}{R_L + R_s}\right)$$

Modeling Inductive Links



To maximize efficiency, find the matched R_L

$$\frac{\partial \eta}{\partial R_L} = 0 \quad \rightarrow \quad R_{L,opt} = R_s \sqrt{1 + \frac{\omega^2 M^2}{R_p R_s}}$$

which results in maximum efficiency

$$\eta_{max,R_L} = \frac{\frac{\omega^2 M^2}{R_p R_s}}{\left(1 + \sqrt{1 + \frac{\omega^2 M^2}{R_p R_s}}\right)^2} = \frac{k^2 Q_p Q_s}{\left(1 + \sqrt{1 + k^2 Q_p Q_s}\right)^2}$$

where

$$Q_i = \frac{\omega L_i}{R_i} \qquad\qquad k = \frac{M}{\sqrt{L_p L_s}}$$

Model Conclusions

$$\eta_{max,R_L} = \frac{k^2 Q_p Q_s}{\left(1 + \sqrt{1 + k^2 Q_p Q_s}\right)^2}$$

- To increase inductive link maximum efficiency, increase $k^2 Q_p Q_s$
  - $k^2 Q_p Q_s = 10{,}000$ for $\eta_{max,R_L} = 98\%$

- Valid for $X_s = -\omega L_s$ and $R_L = R_{L,opt} = R_s\sqrt{1 + \frac{\omega^2 M^2}{R_p R_s}}$
  - Requires varying receiver impedance (magnitude and phase)
  - Difficult to do across varying k and with nonideal rectifier

- η_{max,R_L} is the fundamental limit before considering any implementation of the power electronics

Multi-Receiver Efficiency

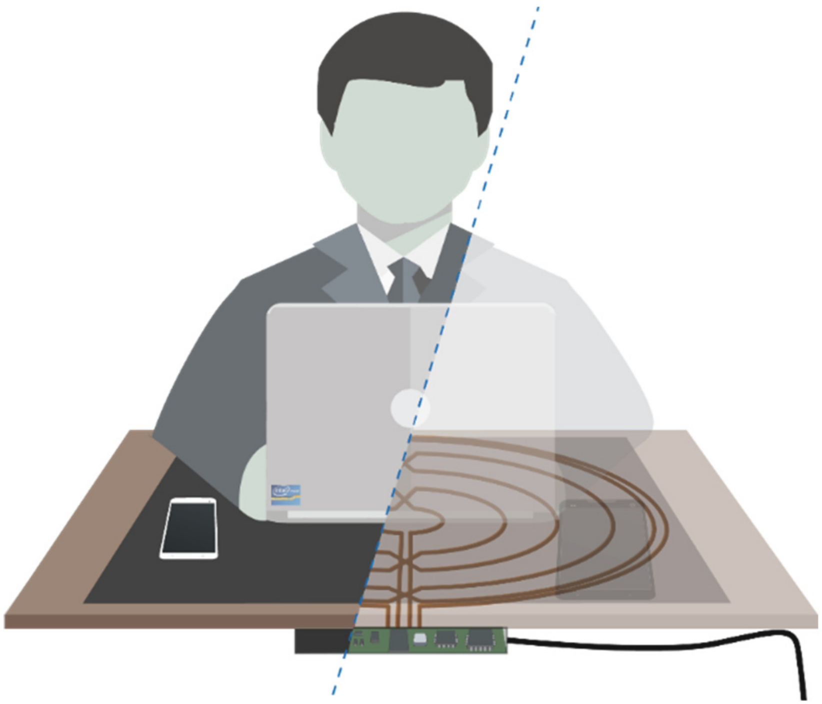
- For N_R identical receivers with no cross-coupling

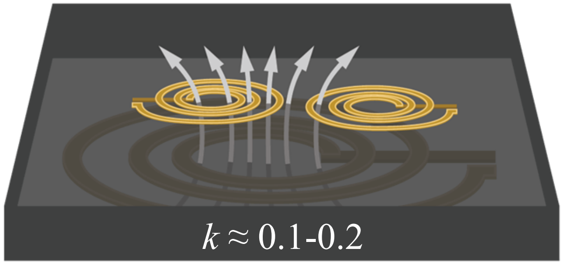
$$\eta_{max} = \frac{N_R k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + N_R k^2 Q_1 Q_2}\right)^2}$$

- Efficiency increases with multiple receivers
- Requires identical coupling and each receiver to regulate resistance to a global optimum

M. Fu, T. Zhang, C. Ma and X. Zhu, "Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 3, pp. 801-812, March 2015.

Example Application Design





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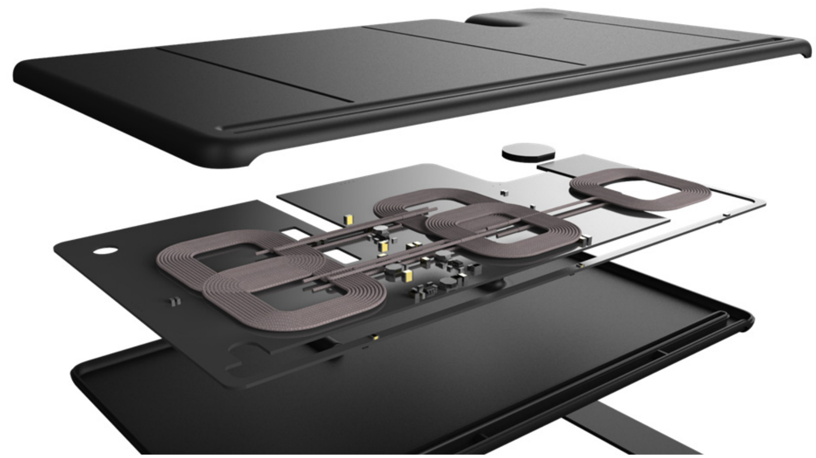
Resonant vs. Inductive WPT

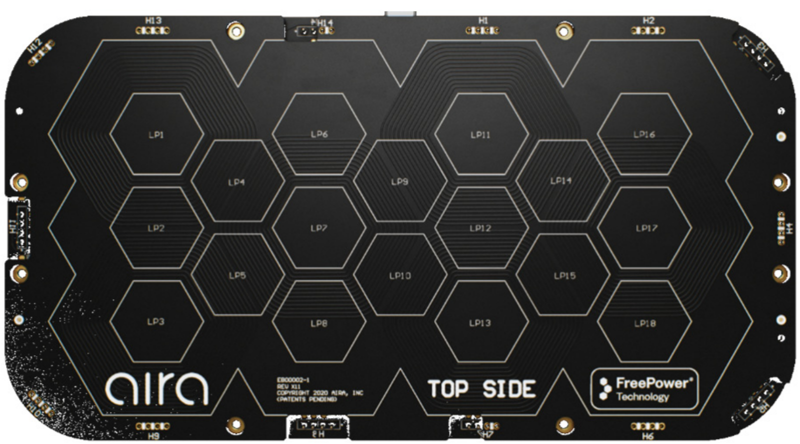
	Inductive single-coil	Inductive multi-coil	Magnetic resonance
Standard	Qi inductive 110-205 kHz		Resonant AirFuel 6.78 MHz
Positioning of receiver application	Exact positioning	Positioning more flexible (X and Y direction)	Free positioning (up to >30 mm vertical freedom)
Number of devices charged	Charges only one device	Charges one device but with better user experience	Charges multiple devices
Rx-Tx communication	In-band communication		Bluetooth low energy or in-band communication

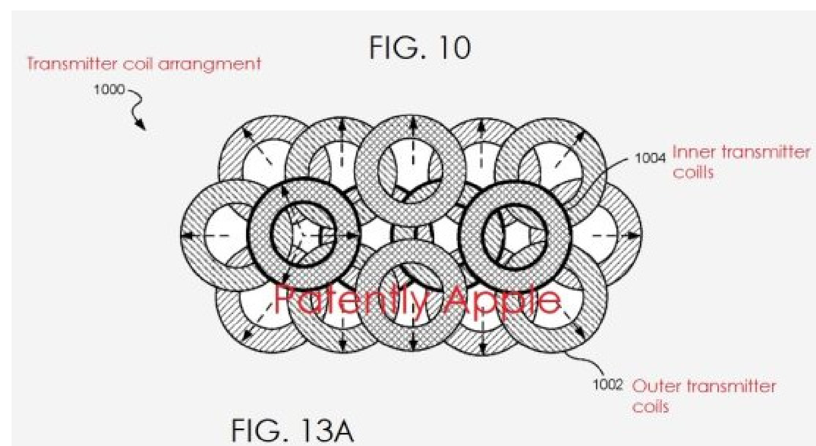
Infineon, “Wireless Charging”, https://www.infineon.com/cms/en/applications/power-supplies/wireless-charging/

Increasing k

- Common approaches
  - Spatial constraints / enforced alignment
  - Multi-coil transmitter
  - Coil and core geometrical design





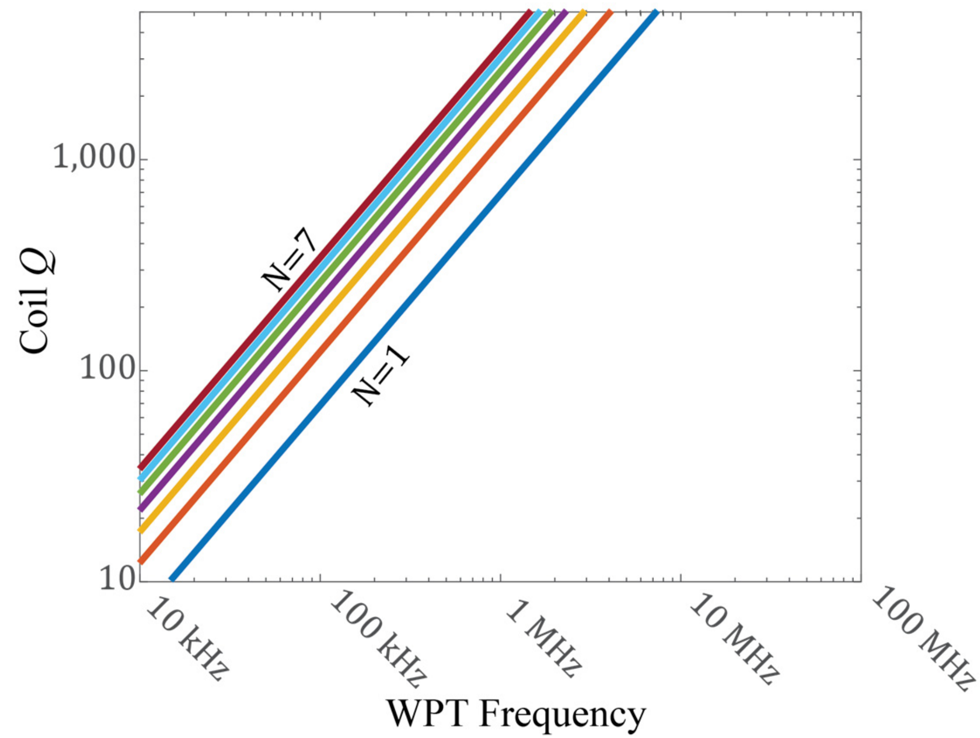


Wyrex, <wyrex.co>
Aria Power <airapower.com>
Apple, Inc. patent via <patentlyapple.com>

Increasing Q

Example case:

- –500 mm coil diameter
- –16 AWG solid wire
- –Proximity loss not considered
- –No core material considered



$$Q = \frac{\omega L}{R}$$

- At low frequency, $R \approx R_{dc}$

$$L = \frac{\mu_0 N^2 (d_{out} + d_{in})}{2} \left(\ln\left(\frac{2.46}{p}\right) + 0.2p^2 \right)$$

$$p = \frac{(d_{out} - d_{in})}{(d_{out} + d_{in})}$$

S. S. Mohan, M. M. Hershenson, S. P boyd, and T. H L.ee, "Simple Accurate Expressions for Planar Spiral Inductances," *IEEE J. of Solid-State Circuits*, 1999

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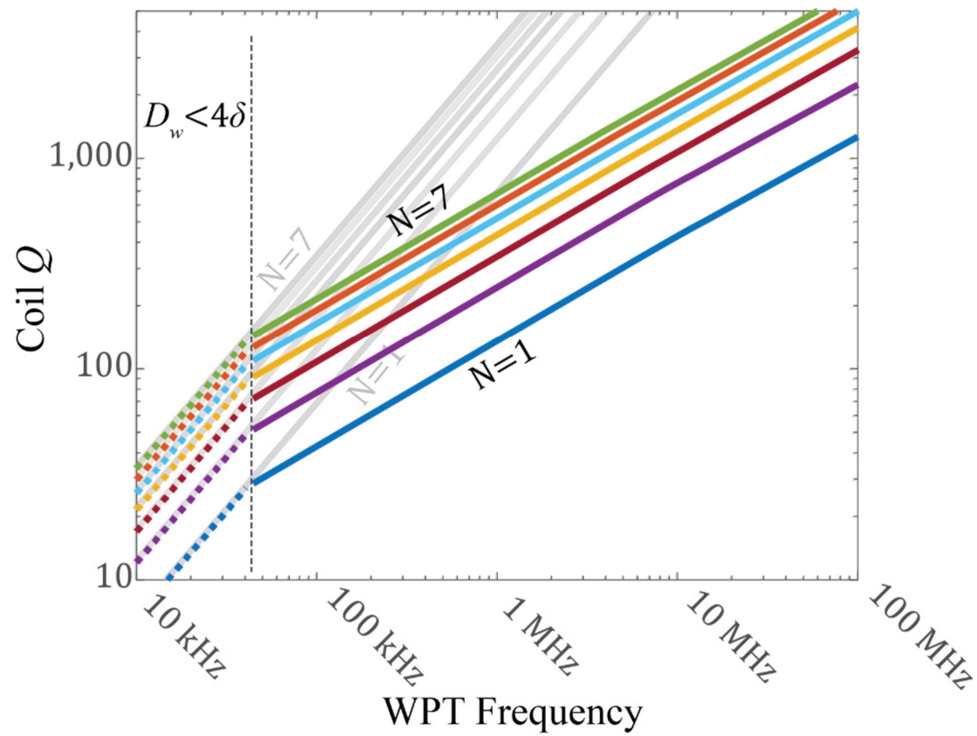

$$Q = \frac{\omega L}{R}$$

- At low frequency, $R \approx R_{dc}$
- Skin depth resistance $R \propto \sqrt{\omega}$
  - when $D_w \gg \delta$

$$\delta = \sqrt{\frac{2\rho}{\omega \mu_0}}$$

$$R_{skin} \approx \frac{\rho L}{\pi D_w} \sqrt{\frac{\rho \omega \mu_0}{2}}, D_w \gg \delta$$

S. S. Mohan, M. M. Hershenson, S. P boyd, and T. H L.ee, "Simple Accurate Expressions for Planar Spiral Inductances," *IEEE J. of Solid-State Circuits*, 1999

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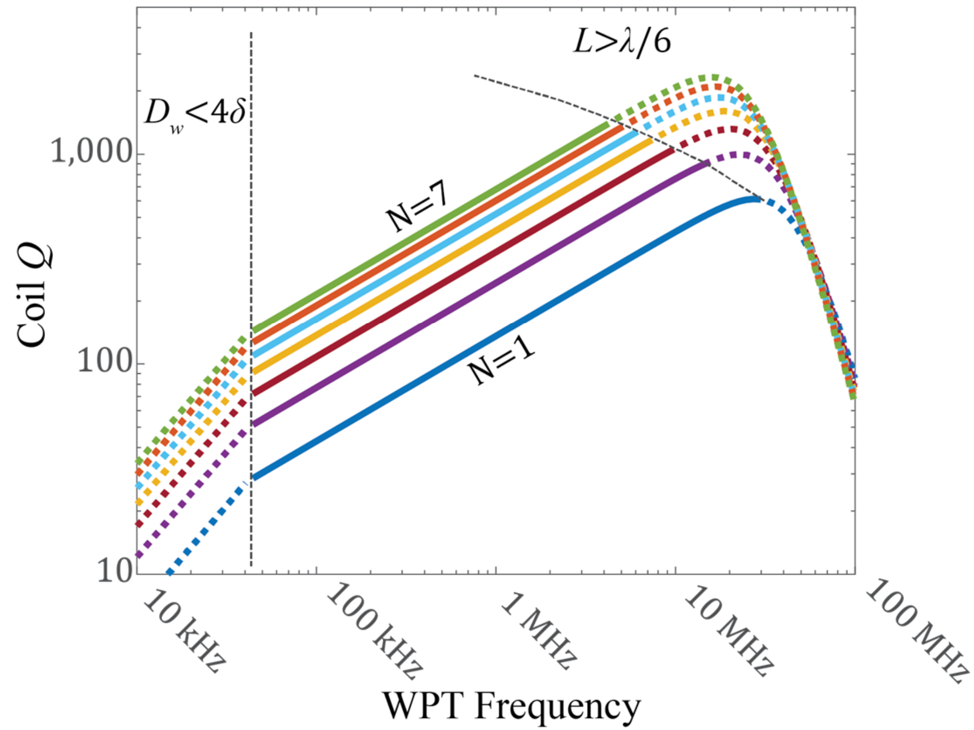

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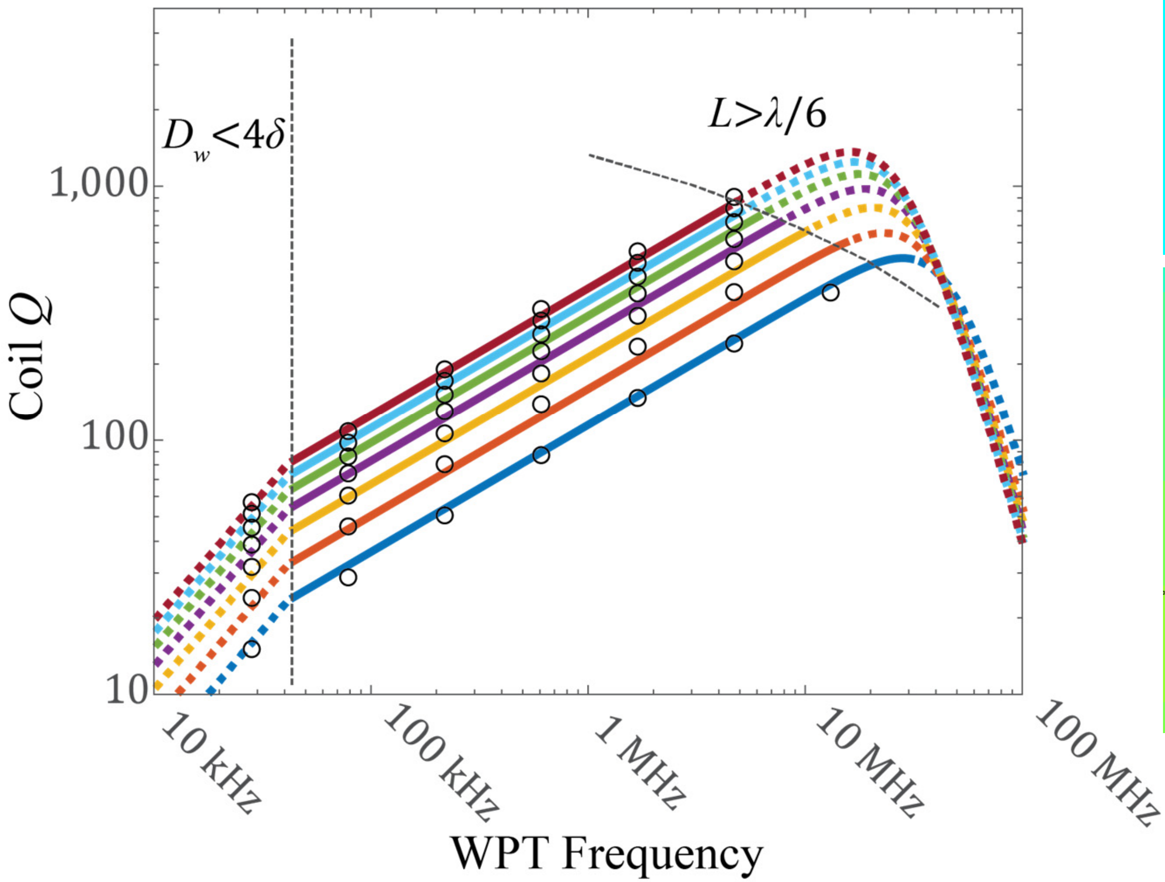
  - when $D_w \gg \delta$
- Radiation resistance $R \propto \omega^4$
  - as $L \to \lambda/4$

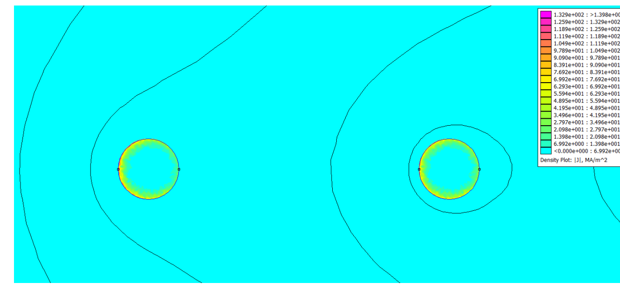
Other HF limits:

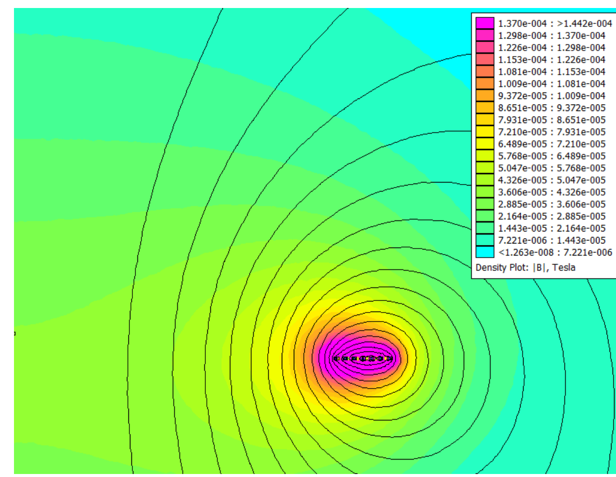
- Parallel capacitance
- Non-coil ac losses

G. S Smith, "Radiation Efficiency of Electrically Small Multiturn Loop Antennas," *IEEE Trans. On Antennas and Propagation*, 1972

FEMM Validation







Litz Wire

Example case:

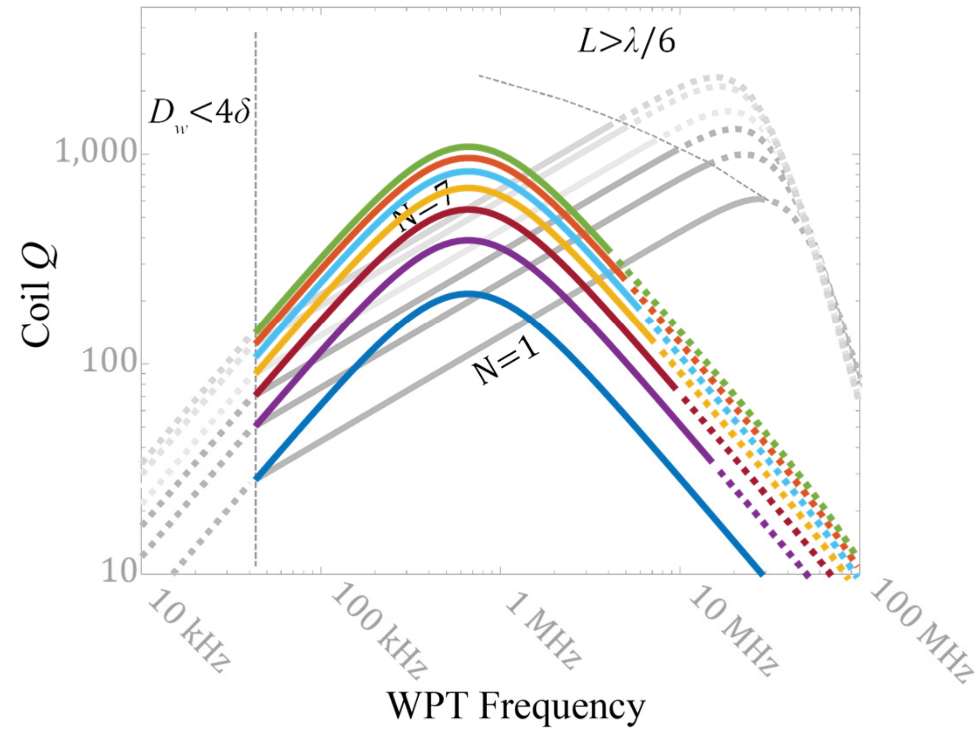
–500 mm coil diameter

–16 AWG solid wire

–Proximity loss not considered

–No core material considered

–**45 AWG** strand Litz



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C. R. Sullivan, "Optimal Choice of Number of Strands in a Litz-Wire Transformer Winding," *IEEE Trans. On Pwr. Elec.*, 1999

Litz Wire

Example case:

–500 mm coil diameter

–16 AWG solid wire

–Proximity loss not considered

–No core material considered

–45 AWG strand Litz

–**52 AWG** strand Litz

$$Q = \frac{\omega L}{R}$$

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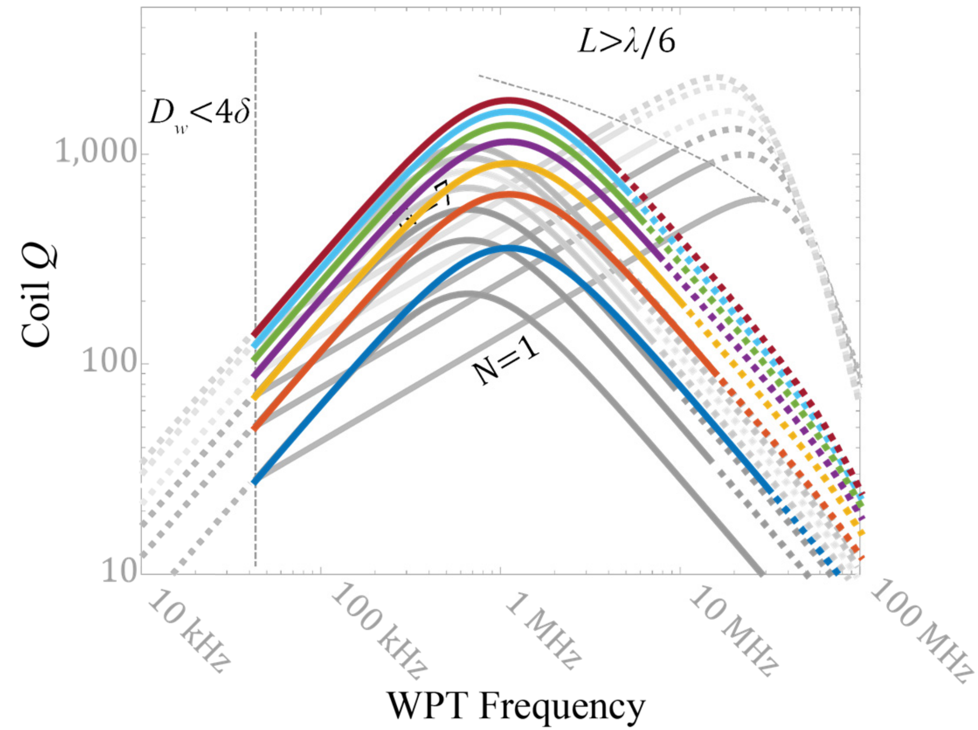

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Litz Wire

Example case:

–500 mm coil diameter

–16 AWG solid wire

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–45 AWG strand Litz

–52 AWG strand Litz

–**10 AWG** solid core

$$Q = \frac{\omega L}{R}$$

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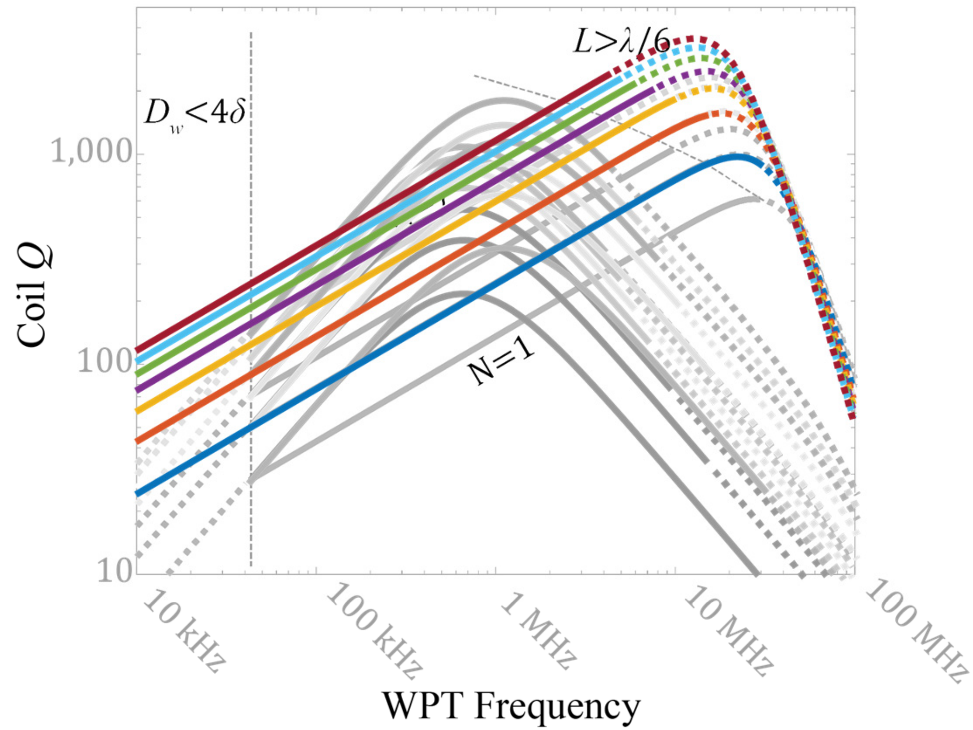

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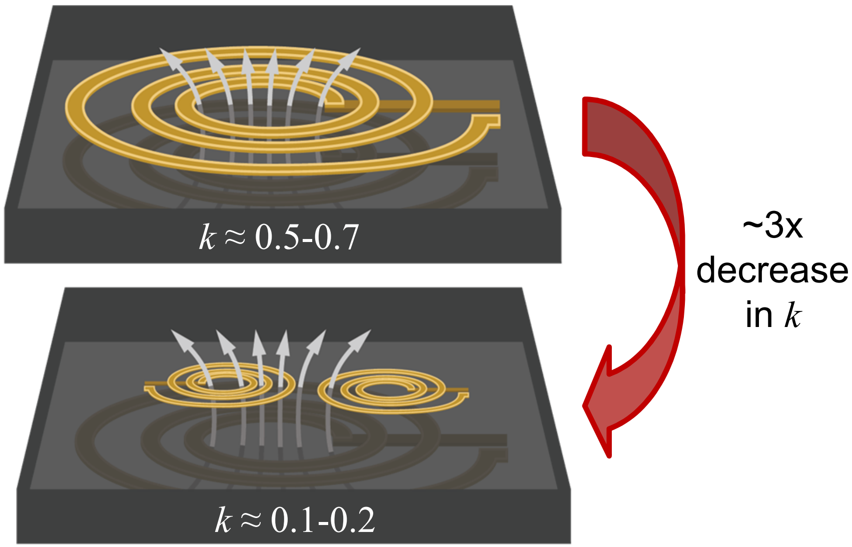
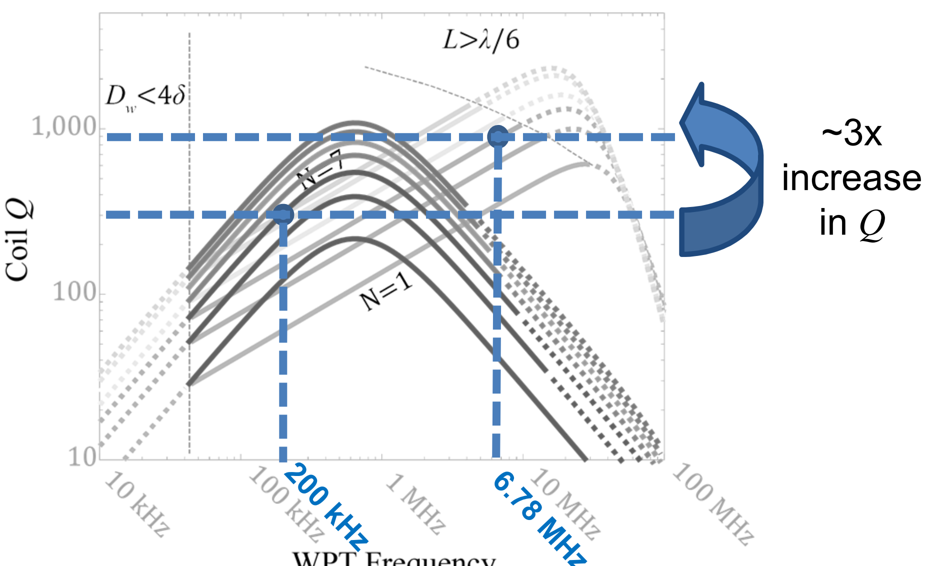
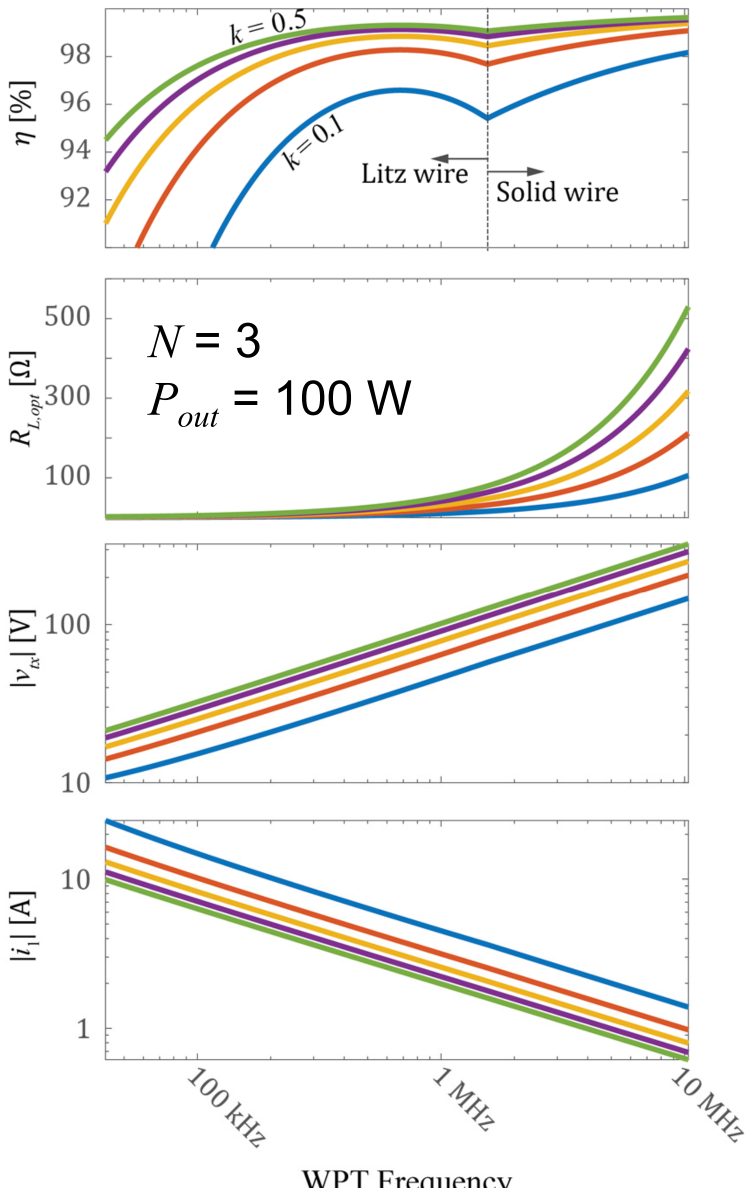
Frequency Selection: Multi-Receiver WPT





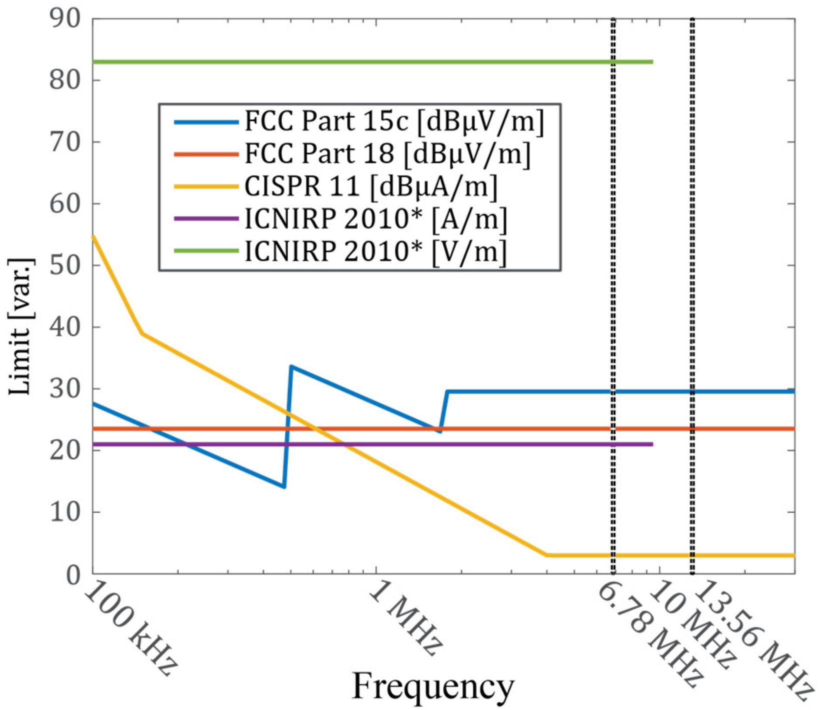
- Higher Q can offset the reduction in η due to low k

Frequency Selection: System Implications



- Higher Q can offset the reduction in η due to low k
- At high frequency, $R_{L,opt}$ increases
  - –High voltage, low current may better-suit power electronics
  - –Requires fast-switching, high voltage power devices

Frequency Selection: Compliance

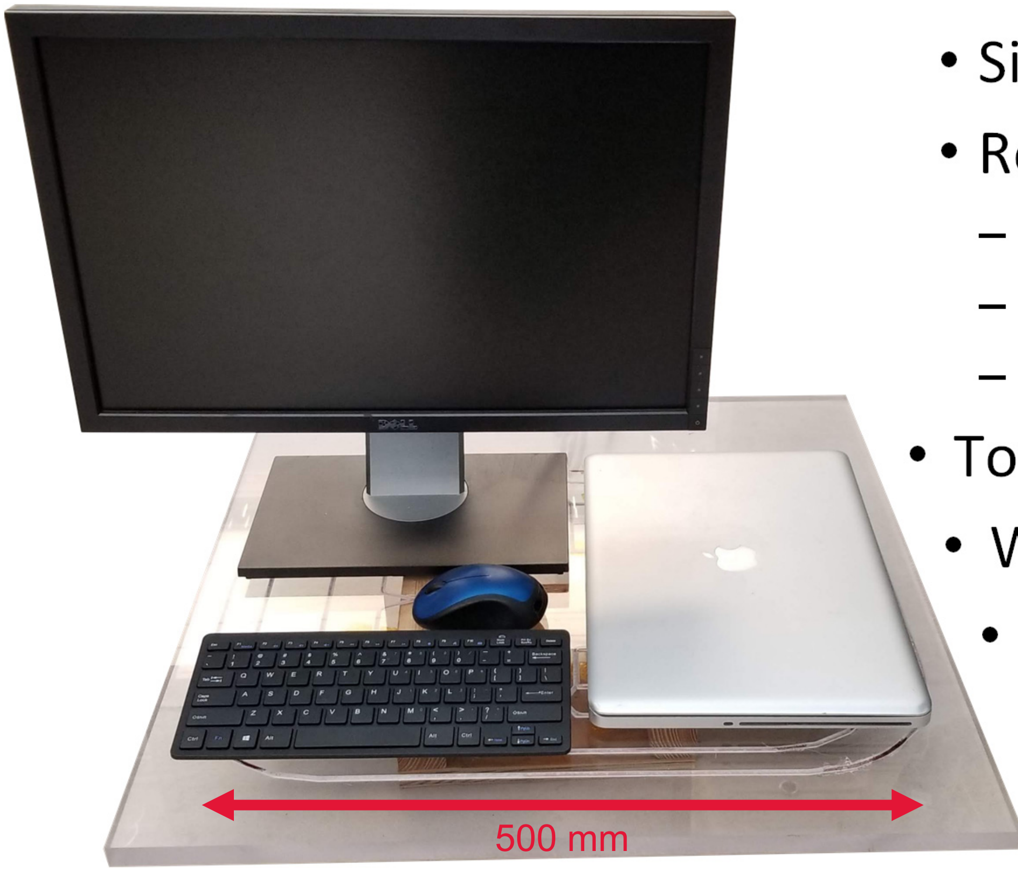


* At frequencies above 100 kHz, SAR limits need to be considered

- Higher Q can offset the reduction in η due to low k
- At high frequency, $R_{L,opt}$ increases
  - –High voltage, low current may better-suit power electronics
  - –Requires fast-switching, high voltage power devices
- Safety and compliance limits favor operation in ISM bands

Uniform Field Transmitter Coil

Multi-Receiver WPT: Target System



- Single transmitter
- Receivers:
  - 25 W Monitor
  - 60 W Laptop
  - 10 W Cell phone
  - ½ W Keyboard
  - ½ W Mouse
- Total $P_{out} \approx$ 100 W
- WPT frequency f_s = 6.78 MHz
- Target $\eta = 90\%$
  - ac line to load dc input

POWERAMERICA

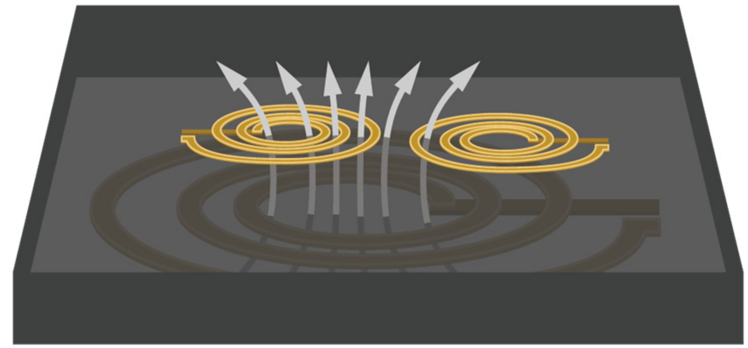
Transmitter Coil Design

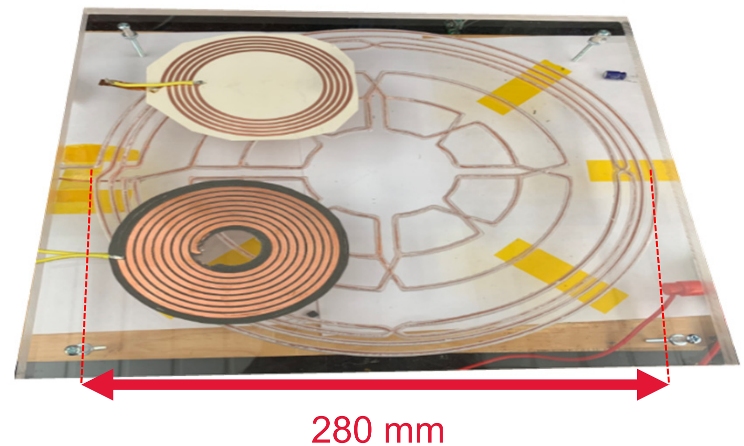
Issues

1. Field, and therefore coupling varies x-y position
2. Reflected load alters inverter output current
   - Cross-regulation issue even without cross-coupling

Approaches

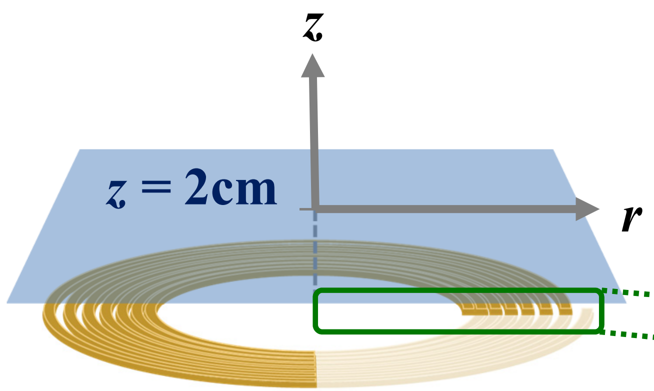
1. Constant-field coil design
2. Constant output current impedance matching network

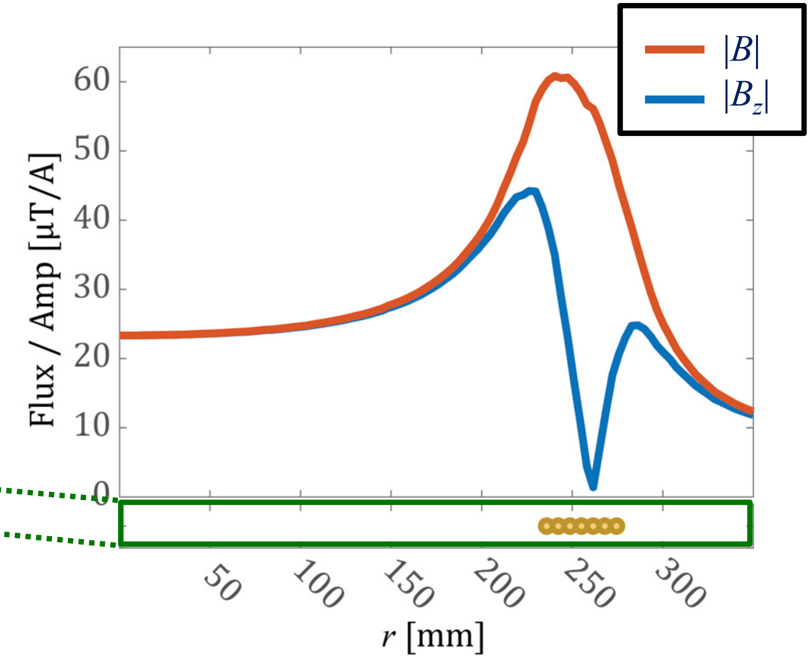




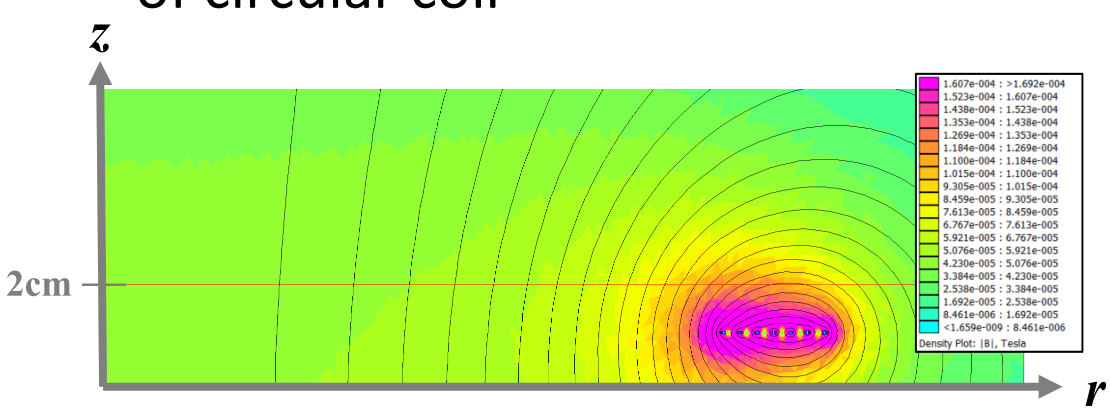
Coil Flux Distribution

- Flux distribution evaluated in FEMM on receiver plane



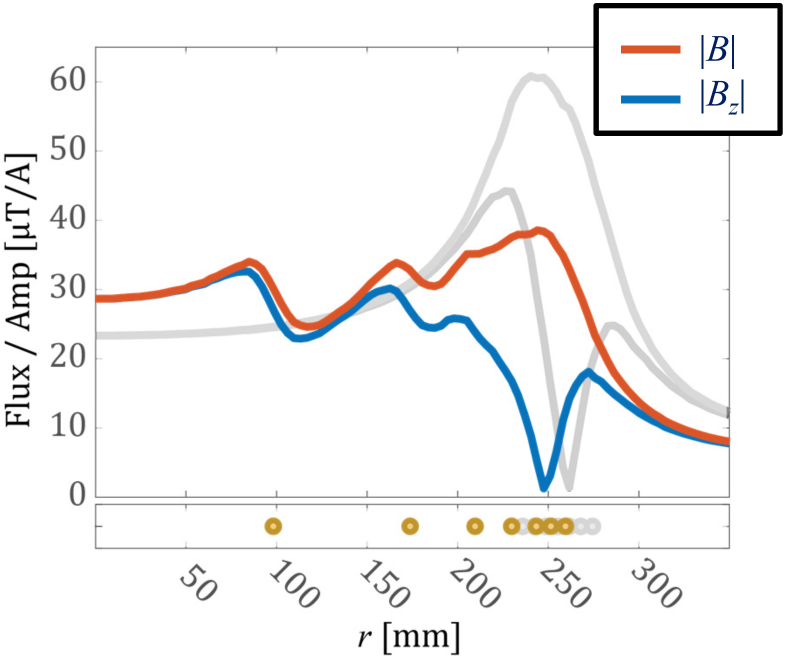


- 2D, axisymmetric simulations of circular coil



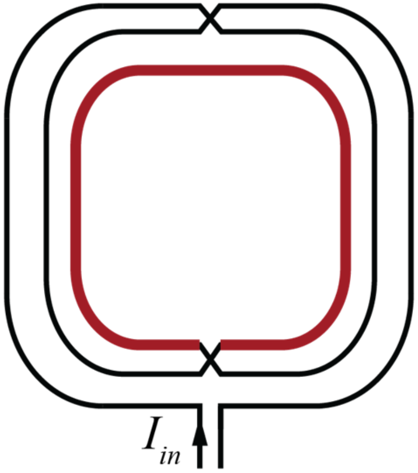
Coil Flux Distribution

- By changing turn radius, can
  - –Reduce variation in $|B_z|$
  - –Reduce peak of $|B|$
- May reduce Q if skin effect is dominant
  - –Inductance can be regained with additional turns while $l \ll \lambda/4$
- Finer resolution field shaping possible with more turns



X. Liu and S. Y. Hui, "Optimal Design of a Hybrid Winding Structure for Planar Contactless Battery Charging Platform," in *IEEE Transactions on Power Electronics*, vol. 23, no. 1, pp. 455-463, Jan. 2008.

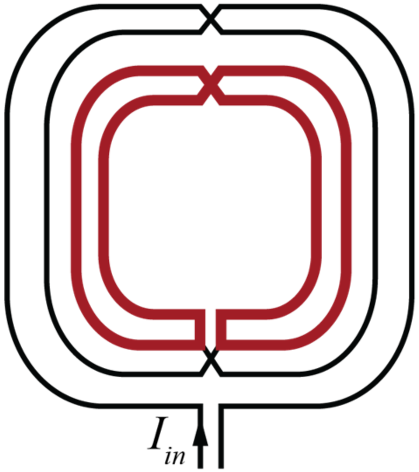
Symmetric Subturns



- 3-turn, symmetric coil
  - Current in each turn:

$$[I_{in} \quad I_{in} \quad \boldsymbol{I_{in}}]$$

Symmetric Subturns

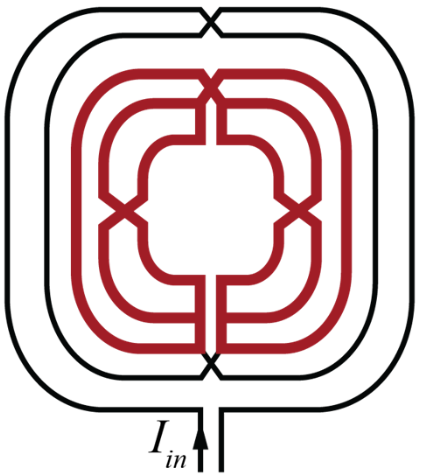


- 3-turn, symmetric coil
  - Current in each turn:

$$\begin{bmatrix} I_{in} & I_{in} & \color{red}{\boldsymbol{\frac{I_{in}}{2}}} & \color{red}{\boldsymbol{\frac{I_{in}}{2}}} \end{bmatrix}$$

- Twisting ensures equal length of each parallel turn
  - Ideally, balanced impedance and equal current sharing

Symmetric Subturns



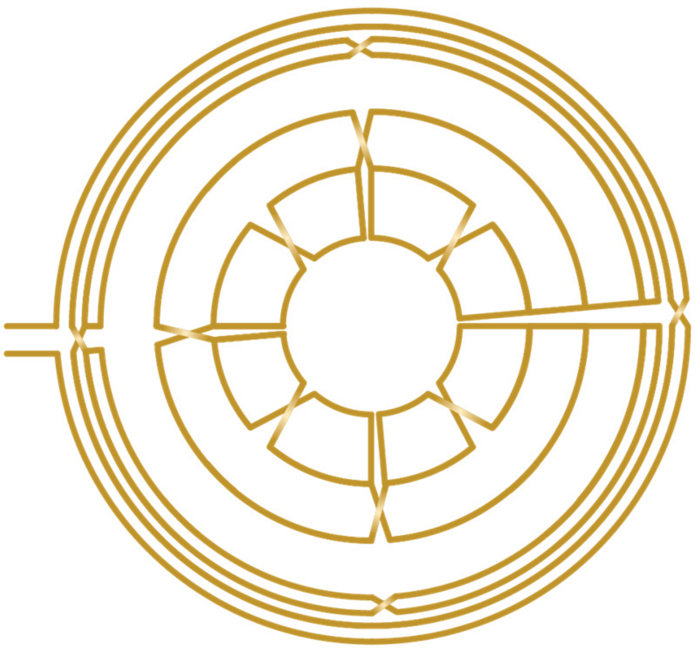
- 3-turn, symmetric coil
  - Current in each turn:

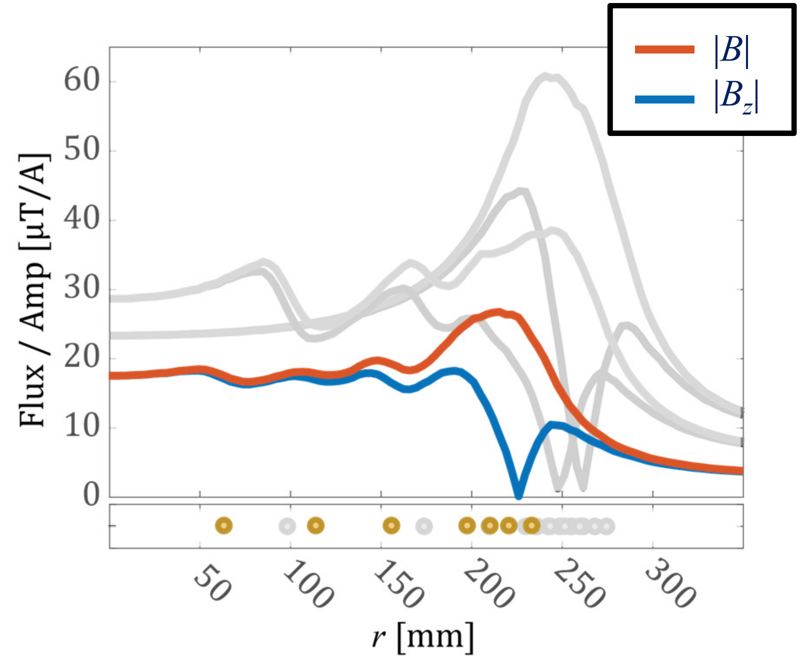
$$\begin{bmatrix} I_{in} & I_{in} & \frac{I_{in}}{2} & \frac{I_{in}}{4} & \frac{I_{in}}{4} \end{bmatrix}$$

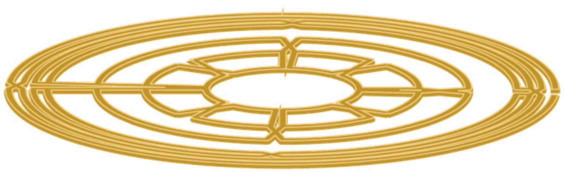
- Twisting ensures equal length of each parallel turn
  - Ideally, balanced impedance and equal current sharing
- Reduced inductance compared to single turn at outer radius
- Much shorter effective length than three discrete turns

Coil Flux Distribution

- Fine resolution field shaping possible with paralleled turns
- “Twisting” necessary to balance impedance between parallel turns

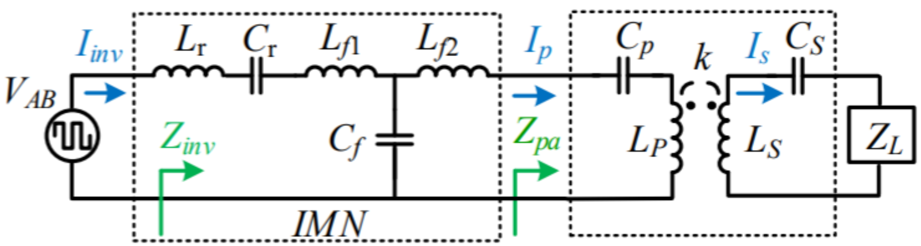






Constant Current IMN

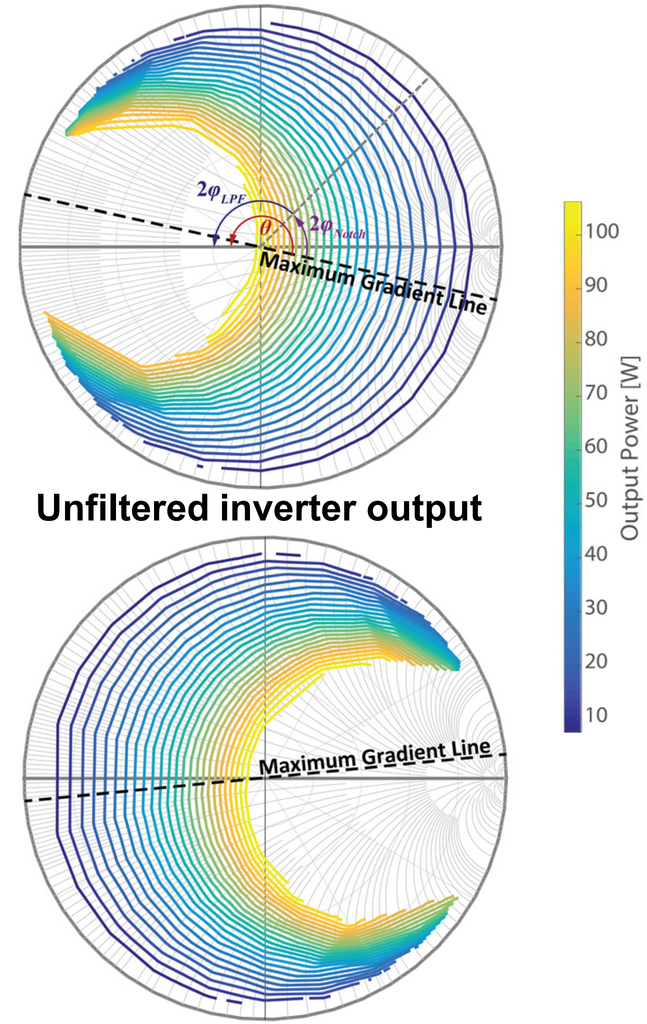
- Impedance matching network between inverter and coils
  - Match reflected load to inverter output characteristic
  - Operate as impedance-admittance converter, i.e. convert output to current source as f_s
  - Additional high frequency attenuation above f_s



- At ω such that $\omega L_{f1} = (\omega C_f)^{-1}$, coil current is

$$I_p = \frac{V_{inv}}{\sqrt{2}(j\omega L_{f1})}$$

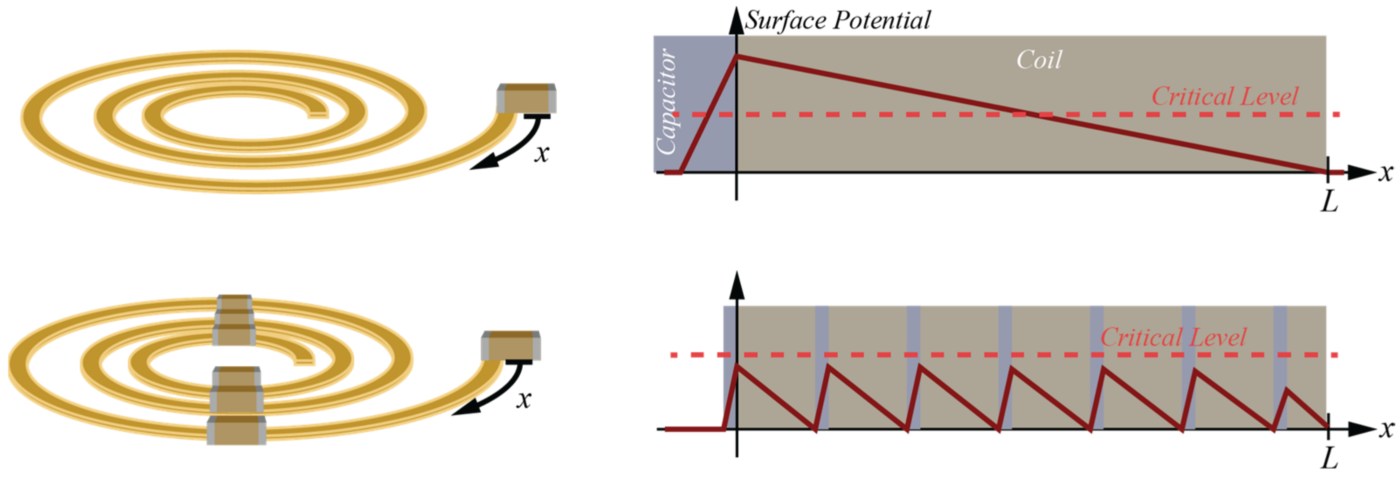
Independent of loading, Z_{pa}



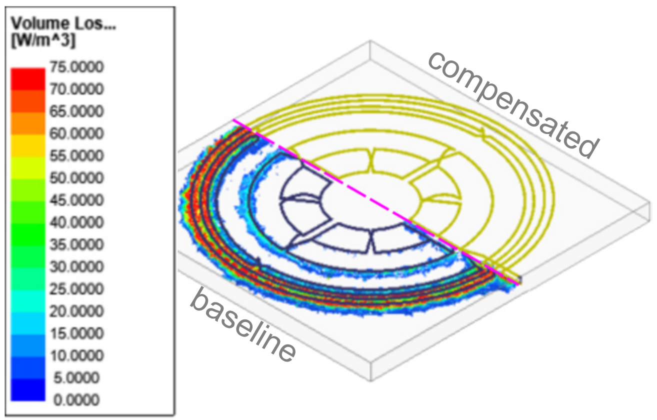
H. Irie and H. Yamana, “Immittance converters suitable for power electronics,” T*ransaction on Industry Electronic Engineering of Japan*, vol. 117-D, no. 8,pp. 962–969, 1997.

L. Jiang, F. Tamjid, C. Zhao, D. Costinett, A. Fathy and S. Yang, "A GaN-based 100 W two-stage wireless power transmitter with inherent current source output," *2016 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, Knoxville, TN, 2016, pp. 65-72.

Electric Field Compensation

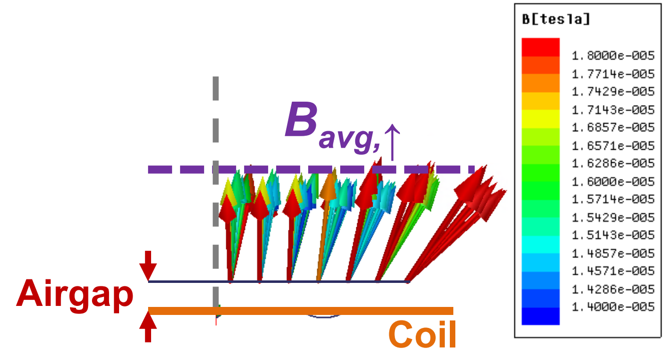


- Longitudinal electric field on coil can cause
  - –Additional dielectric loss
  - –“Ghost touches”
  - –EMI/safety hazard

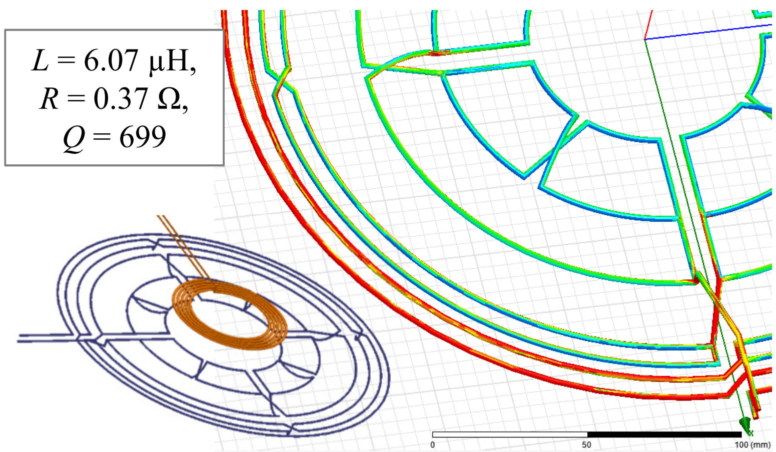


Coil Prototypes

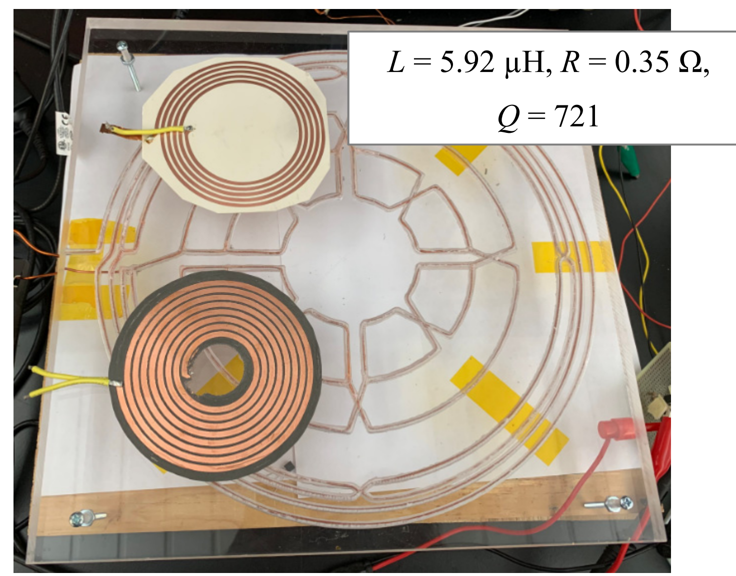
- Design validated with HFSS simulations
  - Negligible radiated power
  - Current balanced between paralleled turns
  - High-Q at 6.78 MHz
- Peak coil-to-coil efficiency of 95%, k<0.1



Field simulation with 2cm airgap

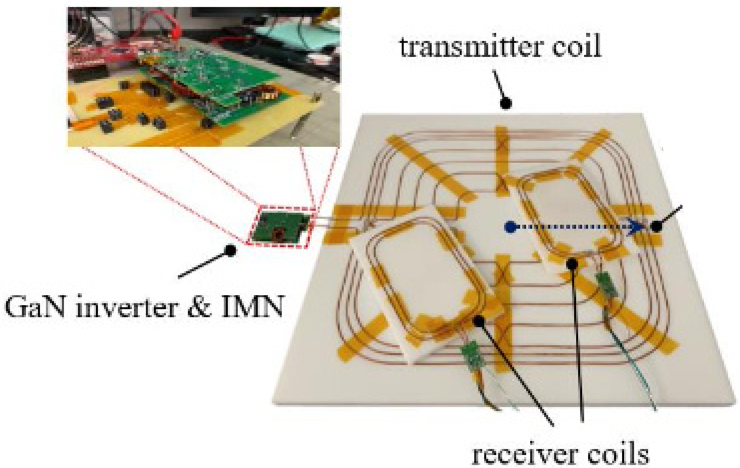


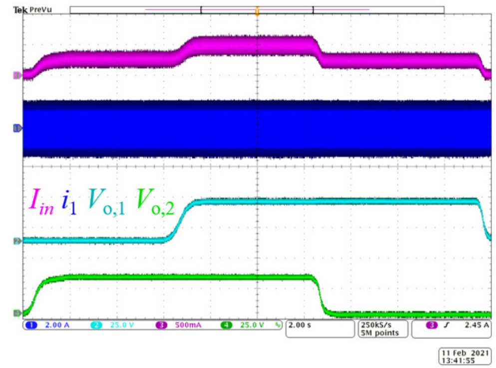
Simulated Tx coil and coil-to-coil model

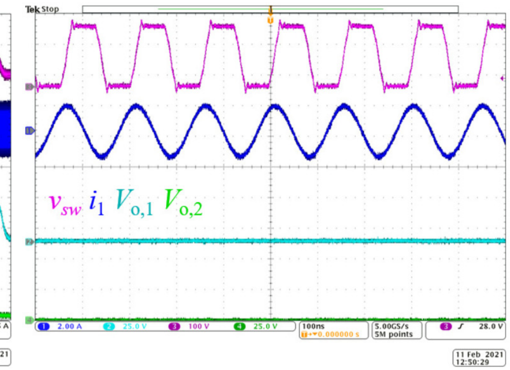


Prototype Tx coil and Rx coils

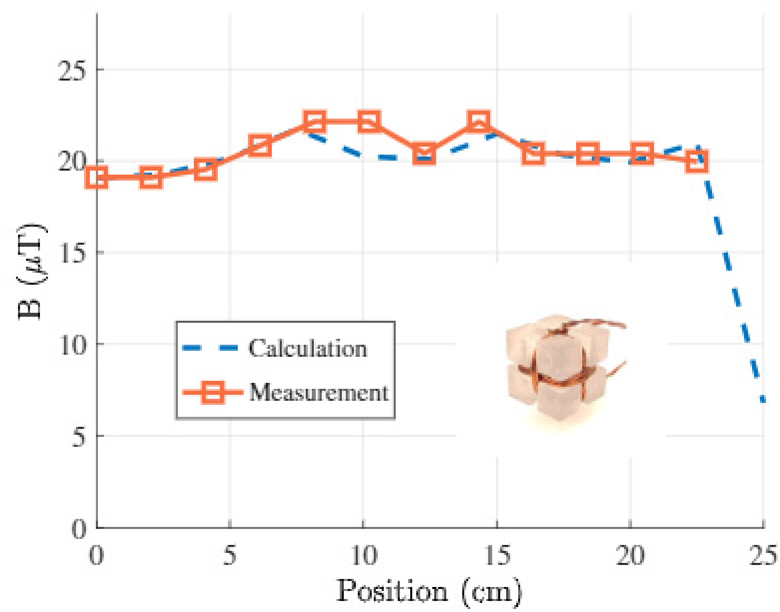
Prototype Validation







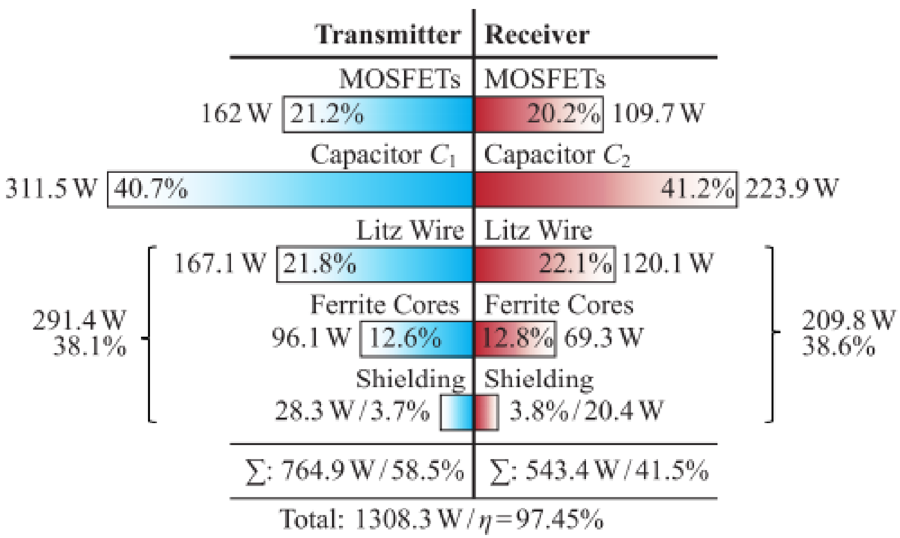
- Excellent B-field uniformity
- 92.8% dc-dc efficiency at 100W
- >90% ac-to-dc efficiency with PFC



Series Self-Resonant Coils

WPT Matching Network

- In low-frequency systems, matching capacitors are large and lossy



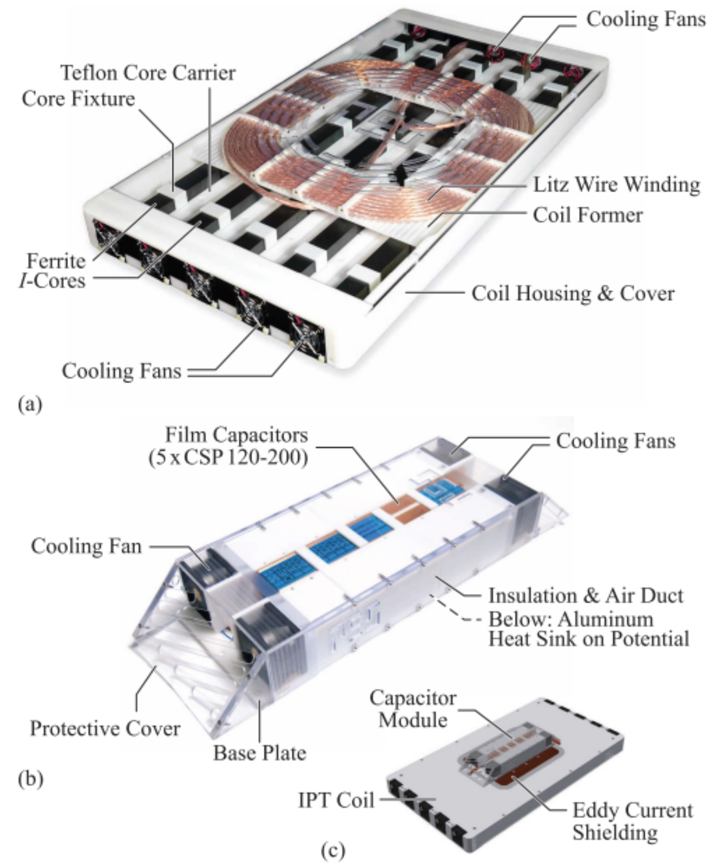
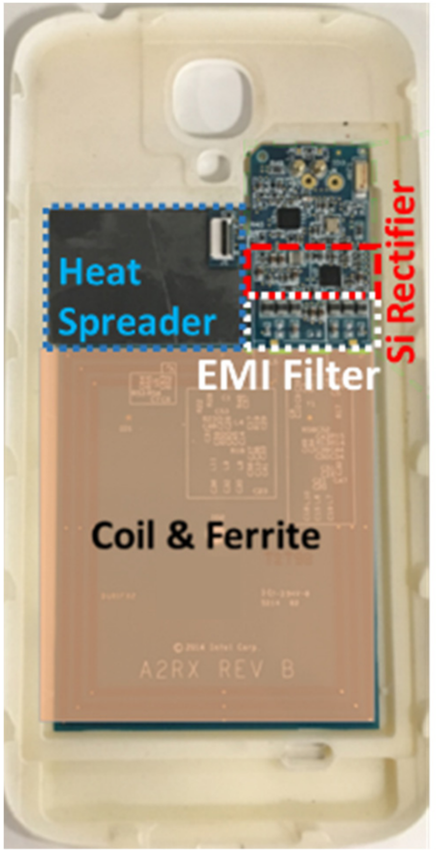


Fig. 8. (a) Photograph of the realized forced-air cooled 50 kW/85 kHz IPT coil prototype (transmitter and receiver coil are identical). (b) Photograph of the resonant capacitor module with forced-air cooling system. (c) Mounting position of the capacitor module at the backside of the IPT coil.

R. Bosshard, J. W. Kolar, "Multi-Objective Optimization of 50 kW/85 kHz IPT System for Public Transport," JESTPE 2016

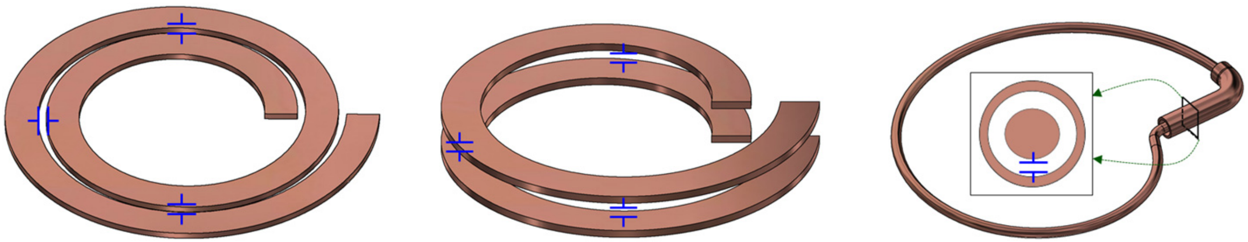
WPT Matching Network

- In low-frequency systems, matching capacitors are large and lossy
- In high-frequency applications, limited receiver-side volume for high voltage components



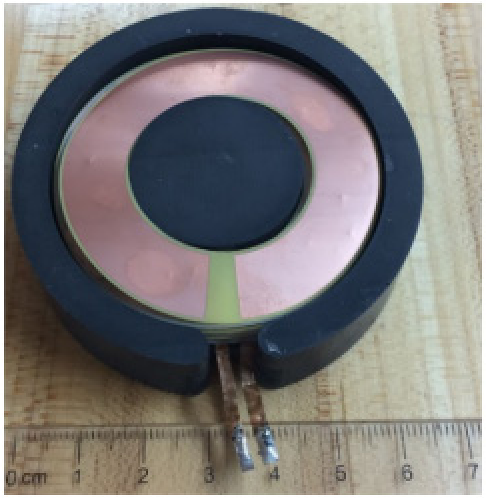
R. Bosshard, J. W. Kolar, “Multi-Objective Optimization of 50 kW/85 kHz IPT System for Public Transport,” JESTPE 2016

Self-Resonant Coils



- Integrate distributed capacitance into large-area coil
- Controlled parasitic series/shunt capacitance
- Possible to employ capacitive ballasting to control current distribution

Parallel Resonant SR Coil



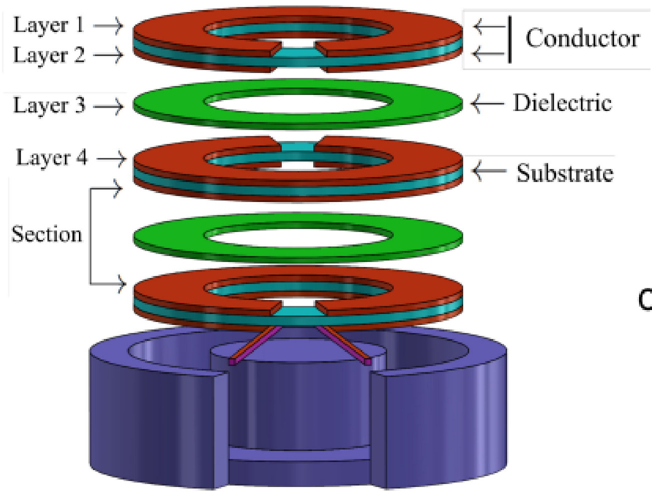
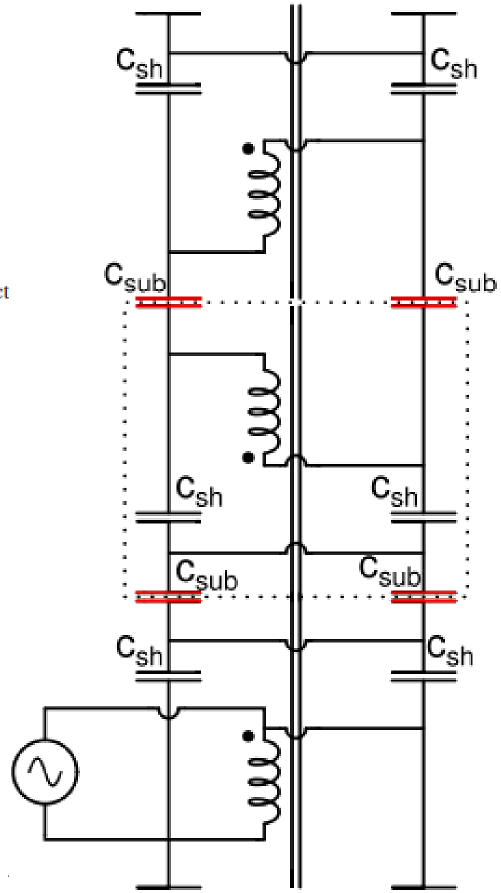


Fig. 7. Layers of a two-section modified self-resonant struct

L=137nH, Q=1183, f_o=7MHz



- Parallel resonant coil
- Uses 96 single-turn foil windings with

$$D \approx 10\mu\text{m} \ll \delta$$

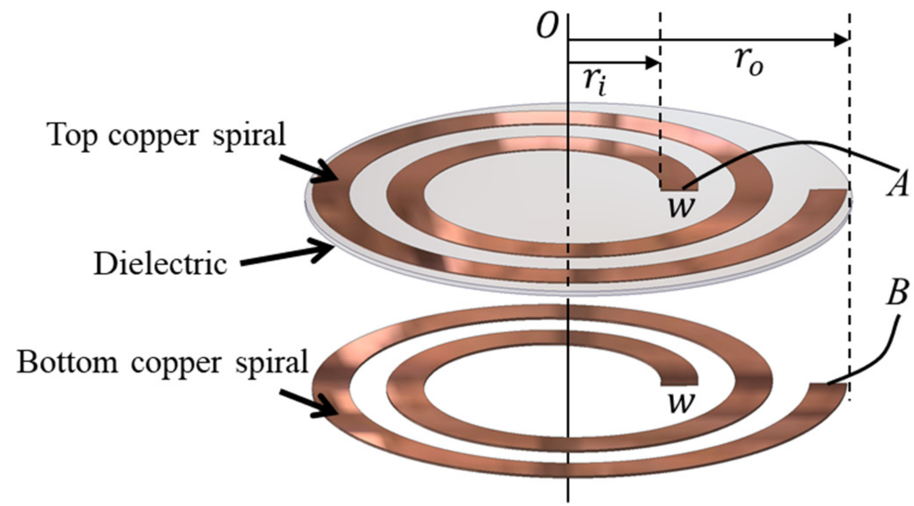
- Highest Q reported in literature for comparable application
- Requires additional impedance matching

A. Stein, P. A. Kyaw, & C. R. Sullivan, "Wireless Power Transfer Utilizing a High-Q Self-Resonant Structure," TPEL

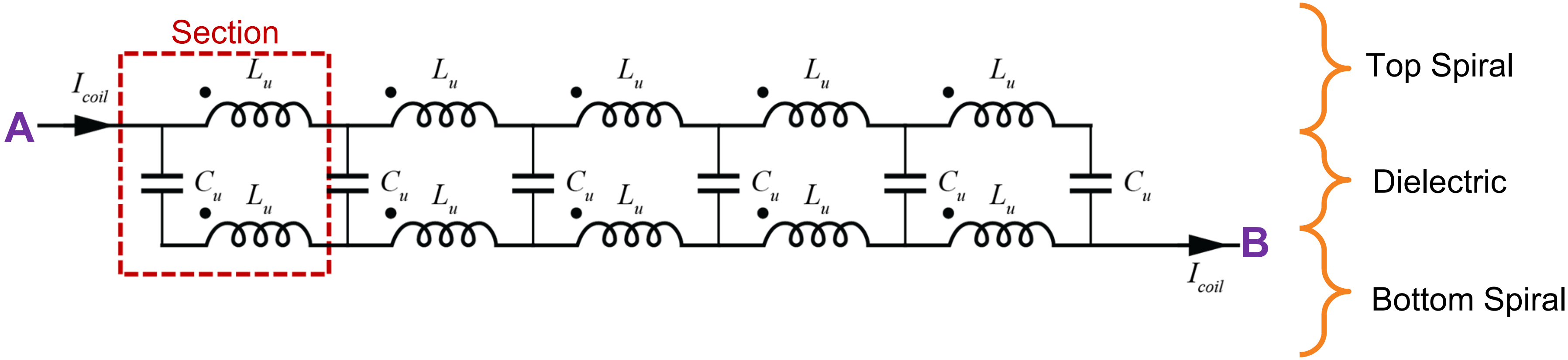
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Series Self-Resonant Coil Structure

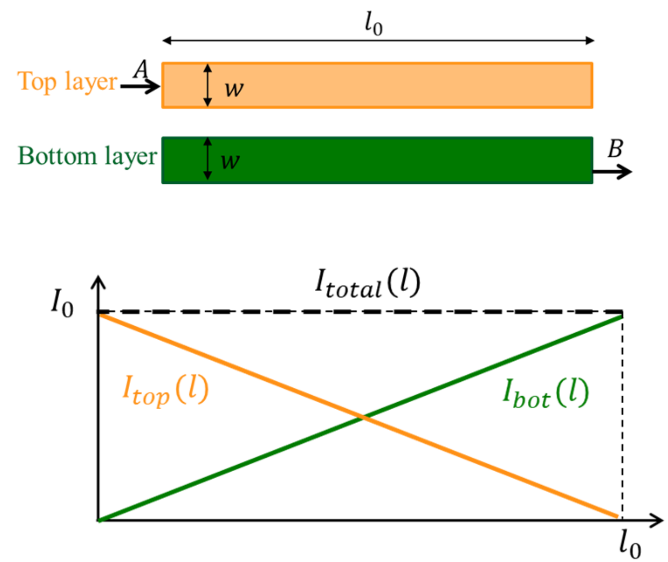
- Multiturn, 2-layer structure
- Low $\tan\delta$ dielectric material used as substrate
- Geometric design determines electrical parameters



Lumped Element Model



- For identical L_u, C_u current transfers uniformly over the length of the spiral
- Every current path traverses the spiral once and crosses dielectric once
  - –Series L-C impedance



Electrical Model

- Inductance

$$L = \frac{\mu_0 N^2 (d_{out} + d_{in})}{2} \left(\ln\left(\frac{2.46}{f}\right) + 0.2 f^2 \right)$$

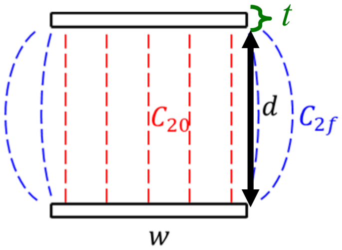
S. S. Mohan, M. M. Hershenson, S. P boyd, and T. H L.ee, “Simple Accurate Expressions for Planar Spiral Inductances,” *IEEE J. of Solid-State Circuits*, 1999

Electrical Model

- Inductance

$$L = \frac{\mu_0 N^2 (d_{out} + d_{in})}{2} \left(\ln\left(\frac{2.46}{p}\right) + 0.2p^2 \right)$$

- Capacitance



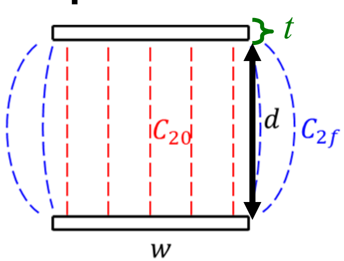
$$C = \frac{\varepsilon_r \varepsilon_0 \pi w N (d_{out} + d_{in})}{2d} \left[1 + \frac{d}{\pi w} \ln \frac{2d}{\pi w} + \frac{d}{\pi w} \ln \left(1 + \frac{2d}{\pi w} + 2\sqrt{\frac{t}{d} + \left(\frac{t}{d}\right)^2} \right) \right]$$

Electrical Model

- Inductance

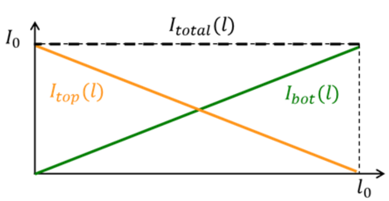
$$L = \frac{\mu_0 N^2 (d_{out} + d_{in})}{2}\left(\ln\left(\frac{2.46}{p}\right) + 0.2p^2\right)$$

- Capacitance



$$C = \frac{\varepsilon_r \varepsilon_0 \pi w N (d_{out} + d_{in})}{2d}\left[1 + \frac{d}{\pi w}\ln\frac{2d}{\pi w} + \frac{d}{\pi w}\ln\left(1 + \frac{2d}{\pi w} + 2\sqrt{\frac{t}{d} + \left(\frac{t}{d}\right)^2}\right)\right]$$

- Resistance

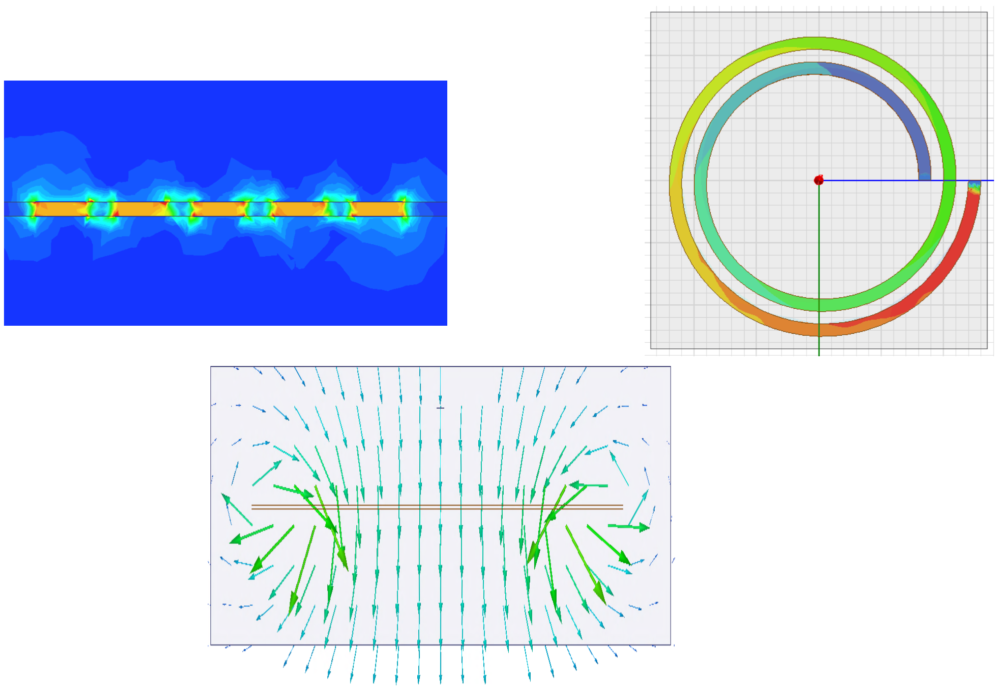


$$R = \frac{2}{3}R_{sprl} + R_{cap}$$

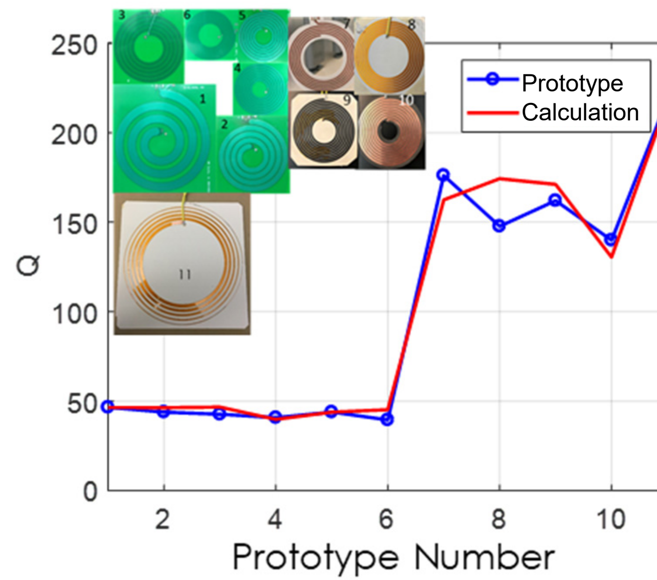
$$= \frac{\rho \pi N (d_{out} + d_{in})}{2wt}\left(\frac{2t}{\delta\left(1 - e^{-\frac{t}{\delta}}\right)} - \frac{4}{3}\right) + \frac{D_k}{\omega C}$$

Series Self-Resonant Receiver Coil

- Axially aligned planar spiral windings with internal dielectric used to generate series self-resonance
- Geometrical optimization required to achieve designed reactance while maximizing Q



FEA of Coil E-field, H-field, and current density



Receiver coil model validation

J. Li and D. Costinett, "Analysis and design of a series self-resonant coil for wireless power transfer," *IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2018, pp. 1052-1059.

Performance Constraints

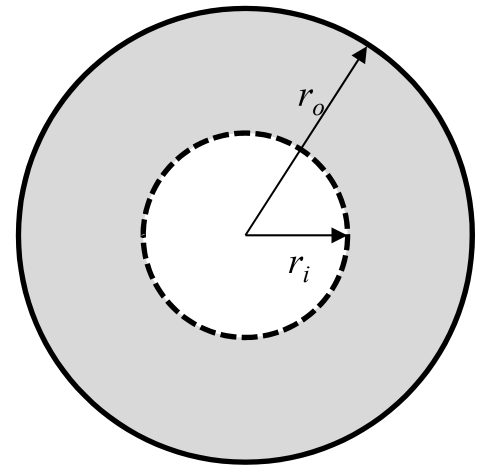
- For a given coil size and dielectric, optimal design is coupled
- Example:
  - Wider traces (w)

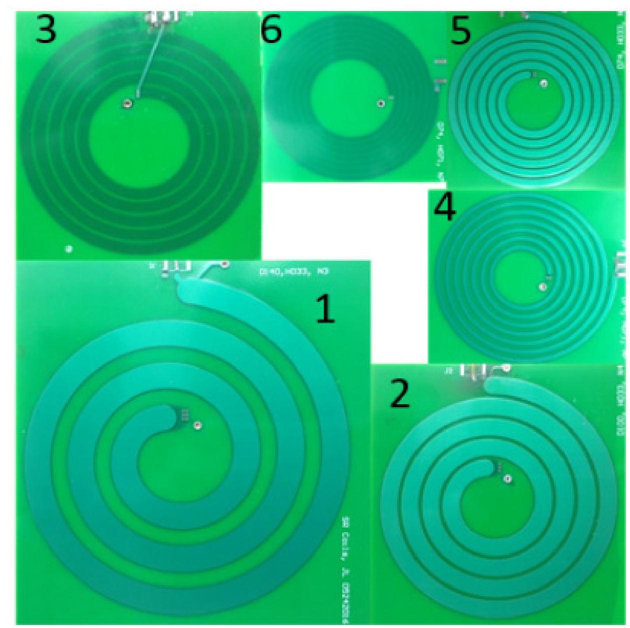
    ↓
  - Reduces resistance

    ↓
  - Increases capacitance

    ↓
  - Requires decreased inductance to maintain resonant frequency

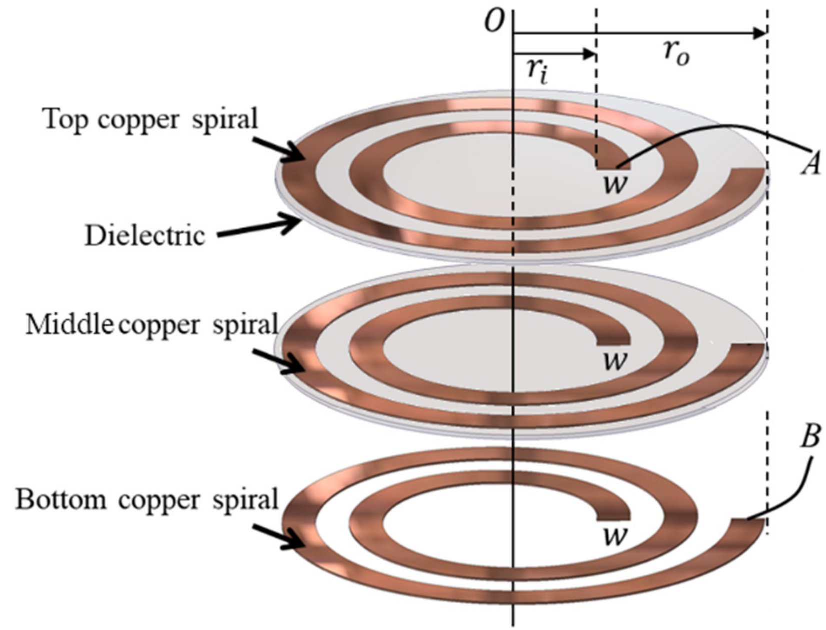
    ↓
  - Q decreases



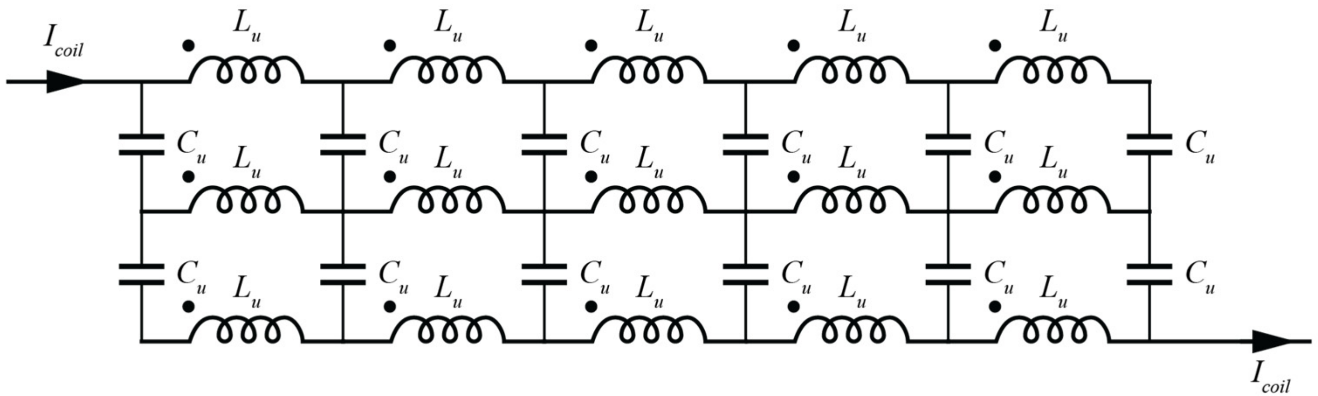


Multi-layer Series Self-Resonant Coil

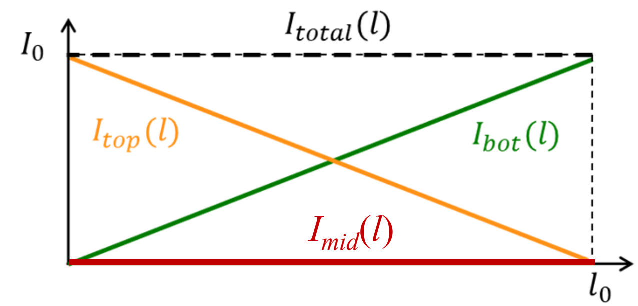
- Goal: use multi-layer series capacitance to allow wider traces, reduce resistance



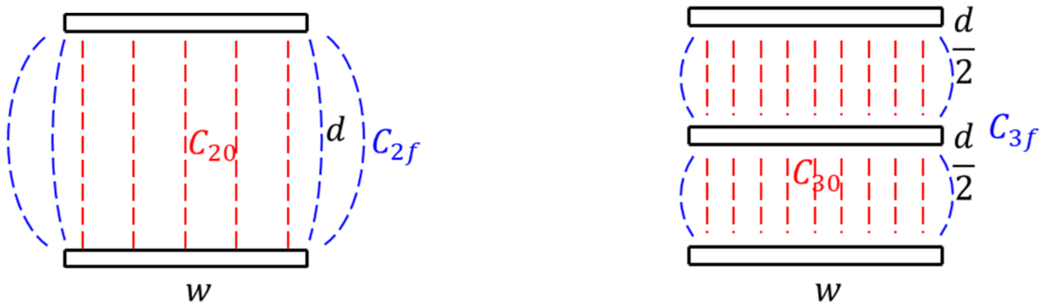
Initial Attempt



- Uniform width design results in no current sharing in middle layer
- Balanced upper and lower capacitances have equal current
- Surprisingly, still some benefit over 2-layer



Fringing



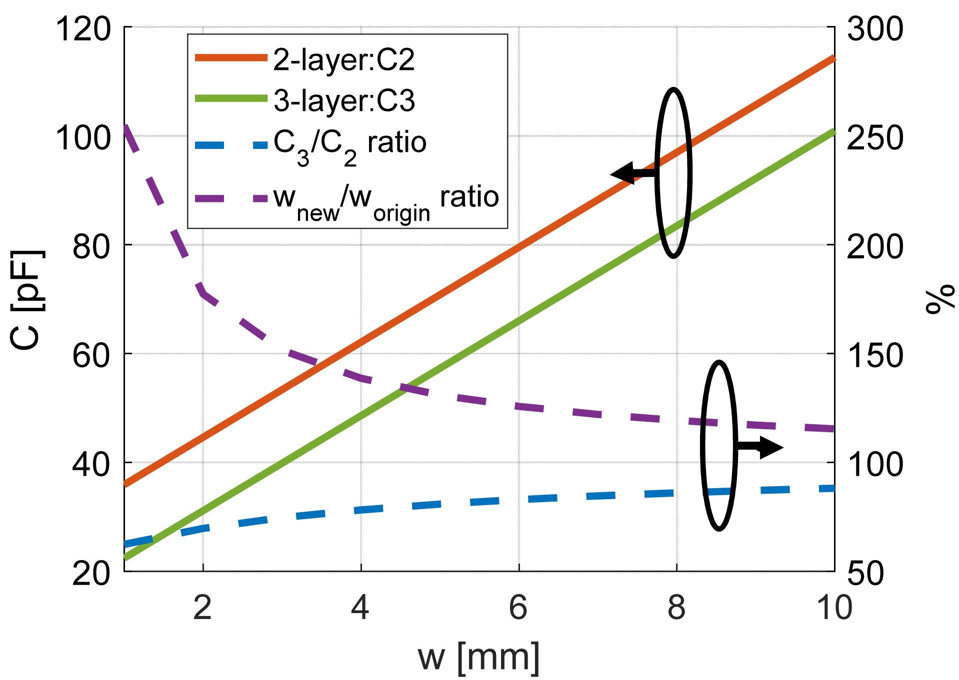
- When $w \gg d$, fringing can be neglected
- When $w \not\gg d$, fringing can dominate parallel-plate capacitance

$$C_2 = C_{20} + 2C_{2f} = \frac{\varepsilon_0 wl}{d} + 2C_{2f}(d)$$

$$C_3 = C_{30} + 2C_{3f} = \frac{1}{2}\frac{\varepsilon_0 wl}{\frac{d}{2}} + 2C_{3f}\left(\frac{d}{2}\right)$$

Impact on Trace Widths

- Due to reduced fringing, the 3-layer design has smaller capacitance than the 2-layer with the same total thickness
- Discrepancy disappears for $w \gg d$
- Wider traces can be used to reduce resistance

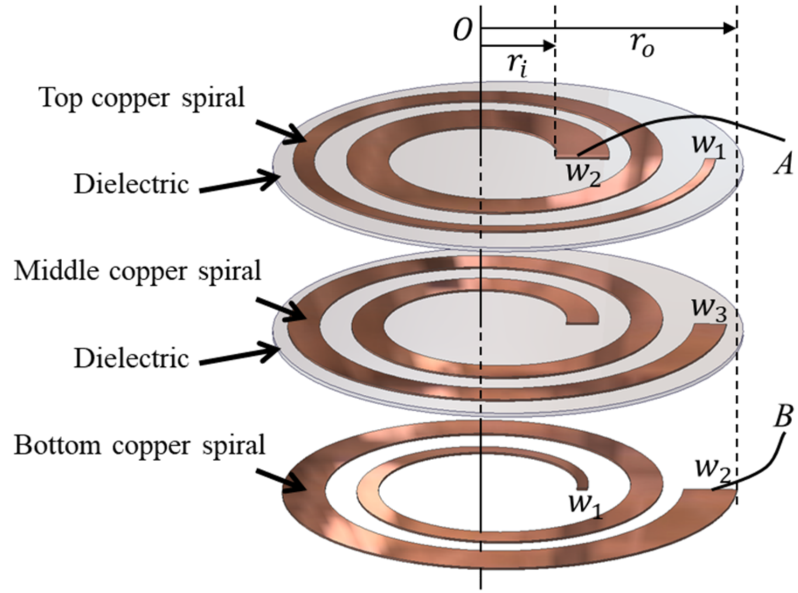


Multi-layer Non-Uniform Series Self-Resonant Coil

- Modification: Allow variable width traces

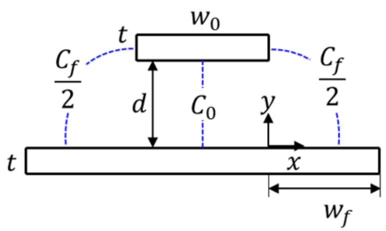
$$w_1 \neq w_2 \neq w_3$$

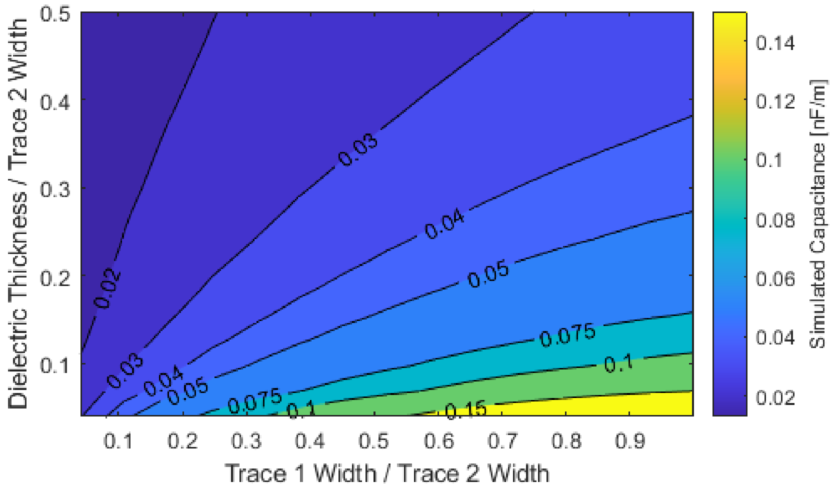
- Trace profile used to control current transfer to subsequent layers

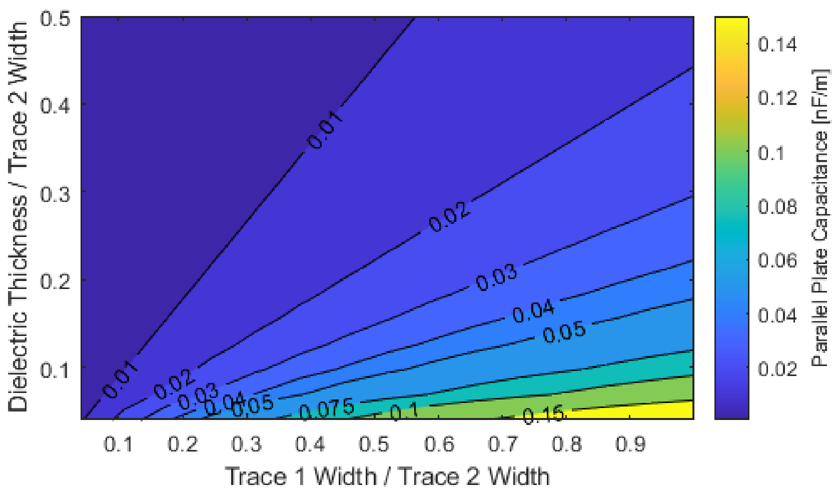


Nonuniform Trace Fringing

- Fringing effect increases with nonuniform trace width







Nonuniform Trace Fringing

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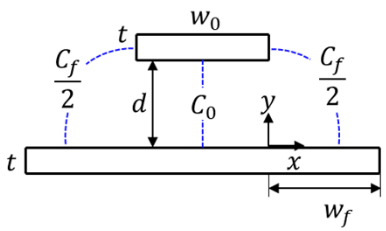
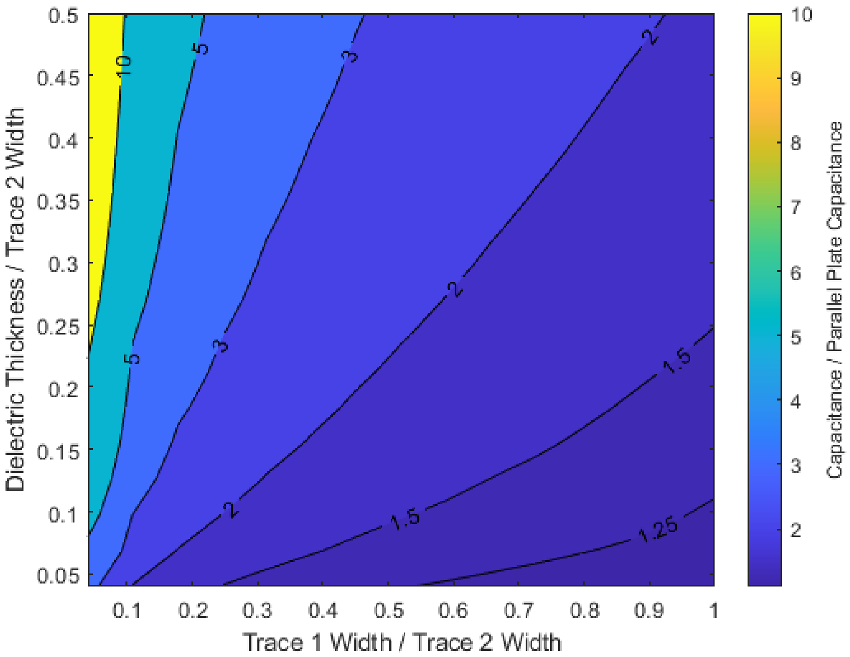
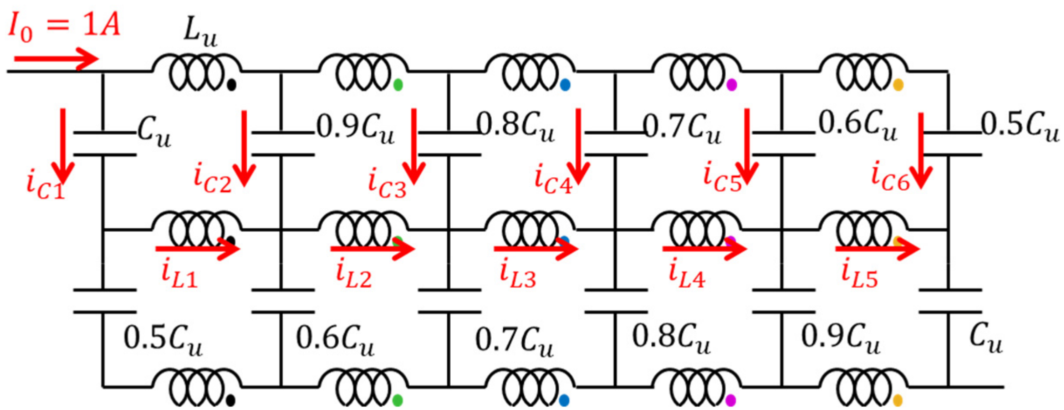
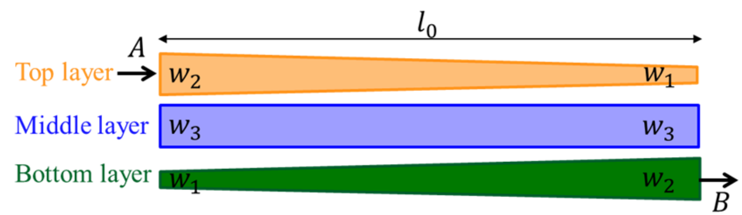


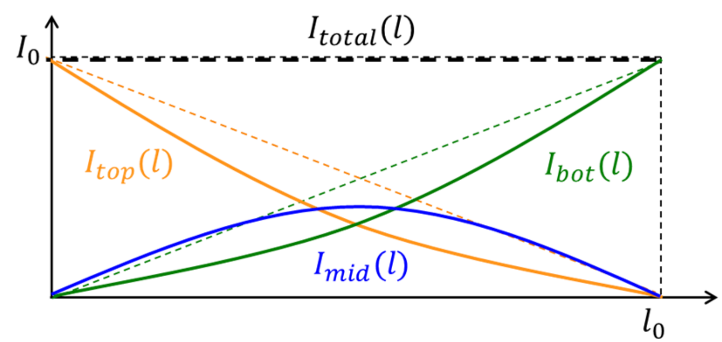


Lumped Element Model

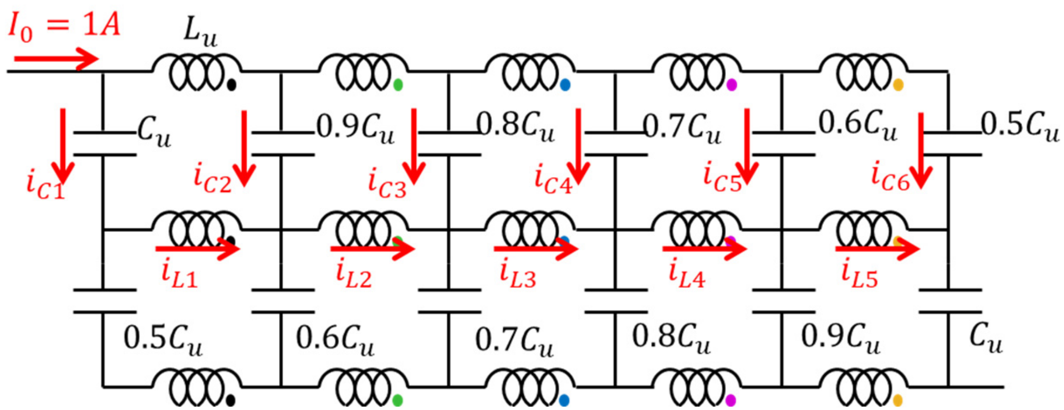


- Differential top-bottom capacitance used to force current through middle layer
- Trace width varies inversely with total current





Lumped Element Model



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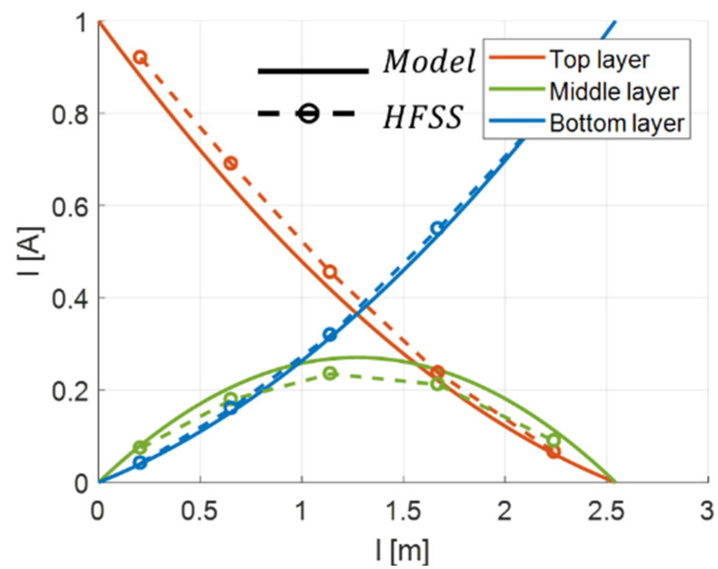


Geometric Design

For: each coil outer radius r_o and f_0

For: each L, C

For: each dielectric and copper material $(d, t, \varepsilon_r, D_k)$

Find $N = N_{min}$, r_i and w_{max} for given L

For: each w_1, w_2 in $[w_{min}, w_{max}]$

Calculate w_3 for given C

Calculate $R = R_{skin} + R_{prox} + R_c$

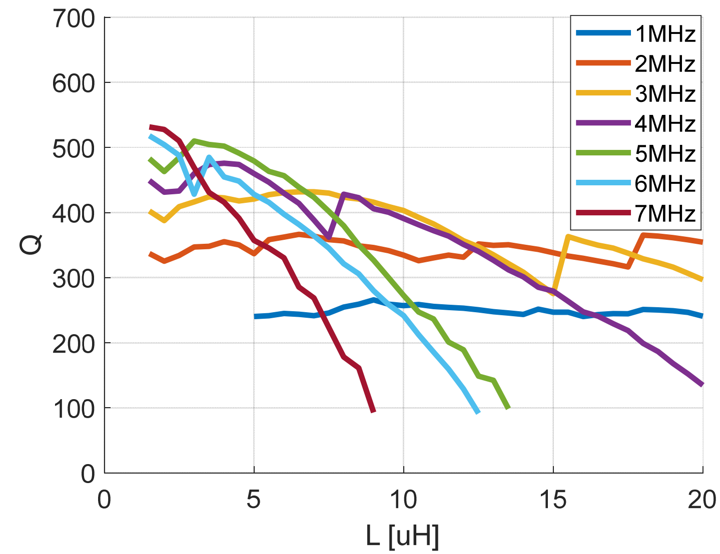
If $R < R_{min}$, update $R_{min} = R$

End

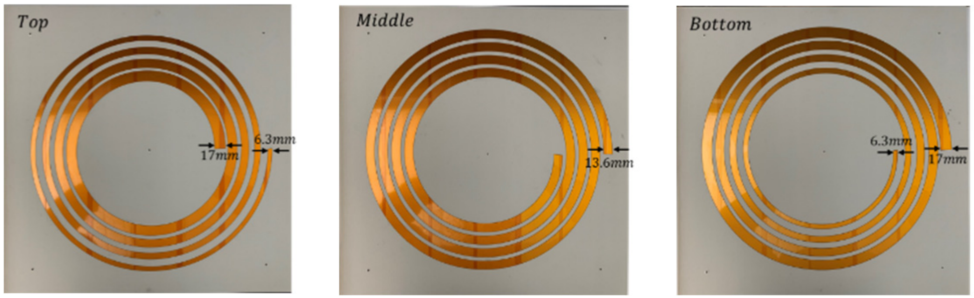
End

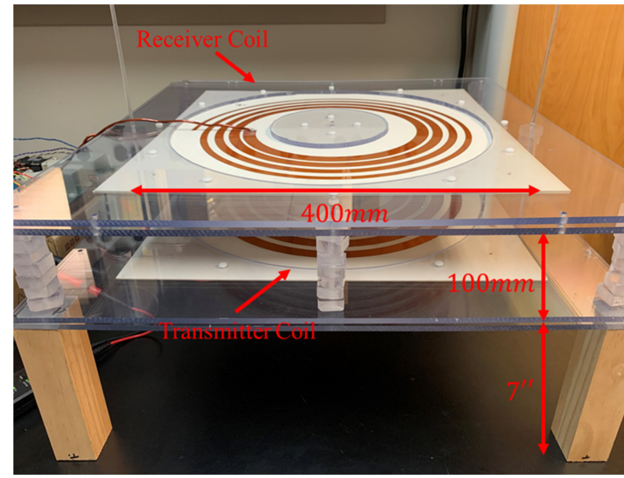
End

End

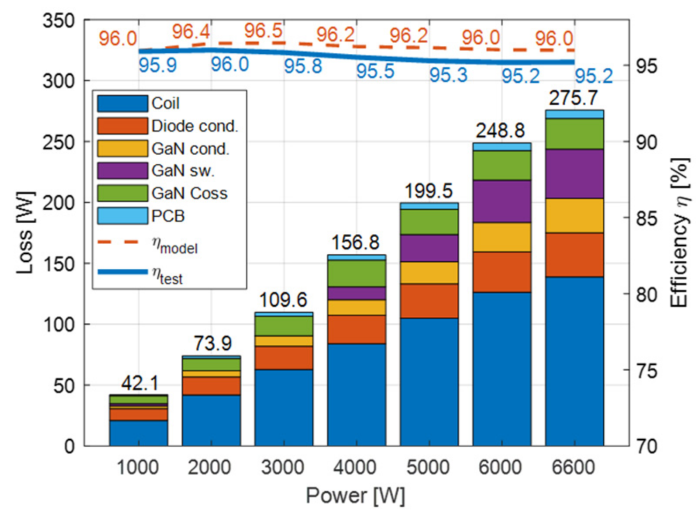


Prototype Validation





L_{tx}=5μH, Q=417, f_o=3MHz
L_{rx}=6.5μH, Q=452, f_o=3.2MHz



- Coil design co-optimized with power stage
- High efficiency, 6.6kW 3MHz system
- High-Q without ferrite