MODELING AND OPTIMIZATION OF MHZ SELF-RESONANT PLANAR COIL FOR WIRELESS POWER TRANSFER

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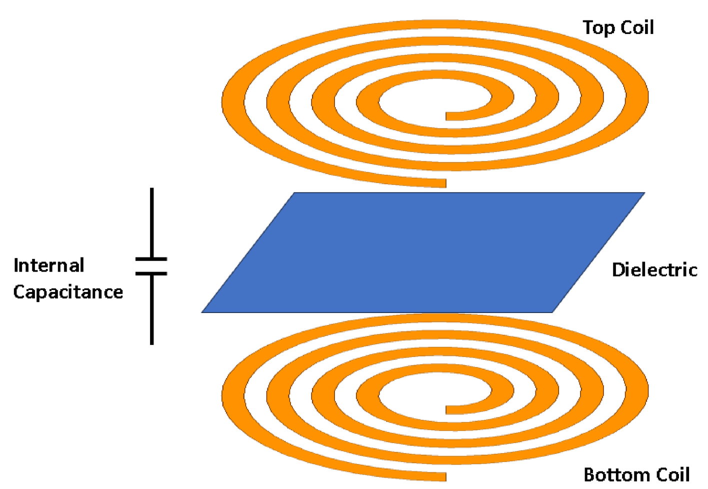
Backgrounds and Motivations

- Rapid EV adoption has pushed a new method for battery charging such as wireless power transfer (WPT)
- Resonance in transmitter (Tx) and receiver (Rx) coils are needed to increase transmission distance and efficiency.
- Existing wireless power transfer coil relies on external capacitor to create resonance which is prone to failure due to very high voltage.
- The need for coils with a very high quality-factor ($Q = X_L/R_s$) to further improve transmission distance and efficiency.

Current Technique

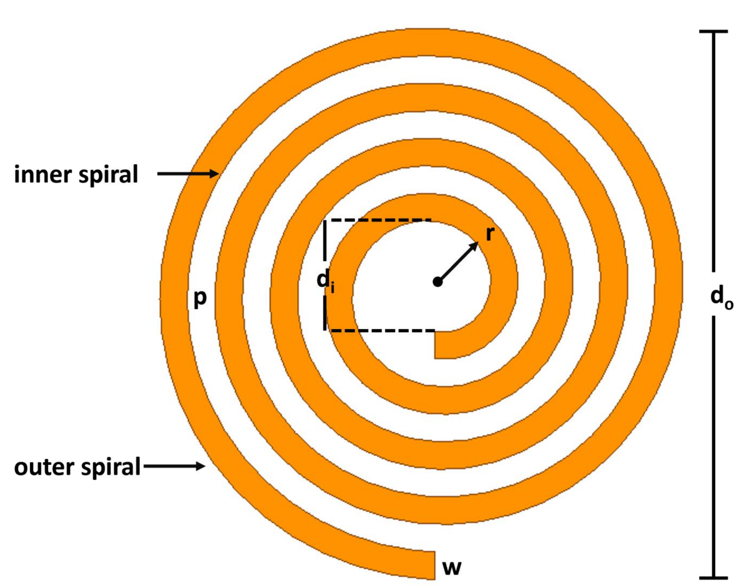
- Open type coil is used due to its property of having internal capacitance.
- The internal capacitance has a higher voltage breakdown rating.
- The use of planar copper sheet to reduce the series resistance R_s to increase Q [1].



Self-resonant Coil

Existing Optimization Method

$$\min R_{r,\text{copper}}(d_i, n, w)$$
$$\text{s.t.} \begin{cases} L_s(d_i, n, w) = L_0 \\ C_s(d_i, n, w) = C_0 \end{cases}$$



Coil's Top View

- Existing method set the inductance, capacitance, and dielectric thickness as fixed values.
- Inner diameter d_i, number of turns n, and coil's width w are set as the decision variables.
- Coil's pitch p (the distance between adjacent turns) is not considered for optimization.
- The optimization will find the minimum series resistance for the coil given all the constraints and design conditions.

New Method for Planar Coil's Modeling and Optimization

- New coil modeling allow us to include coil's pitch into the optimization
- The coil is modeled as two spirals (inner and outer) with initial radius value (r_{i0} and r_{o0}) and constant C that defines the speed of radius growth along angle θ.
- The new equation for coil's L, R_s, and C_s are then derived.

$$r(\theta) = r_0 + C\theta$$

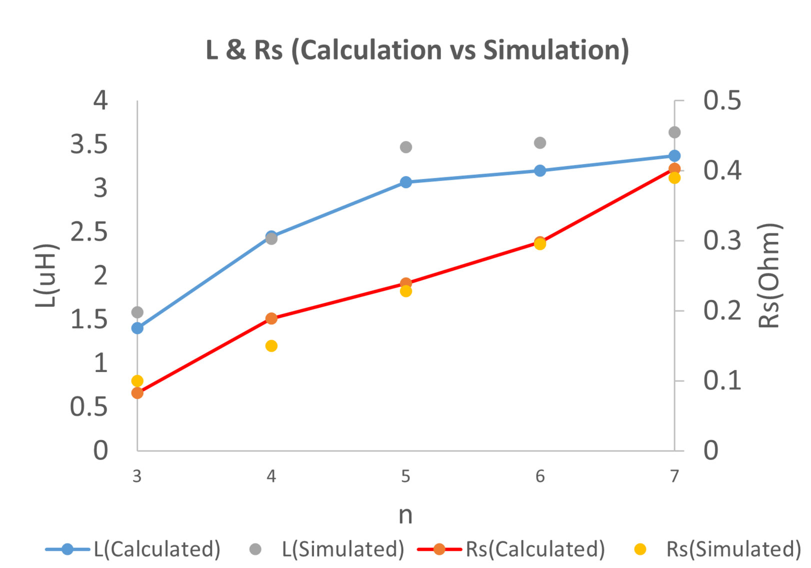
$$Q = \frac{3\mu t_{\text{eff}} f n}{4\rho}(r_{o0} - r_{i0}) \left[\ln\left(\frac{2.462(2(r_{i0} + r_{o0}) + \pi C(4n-1))}{2(r_{o0} - r_{i0}) + \pi C(4n-3)} \right) + 0.2 \left(\frac{2(r_{o0} - r_{i0}) + \pi C(4n-3)}{2(r_{i0} + r_{o0}) + \pi C(4n-1)} \right)^2 \right]$$

- The new optimization will find the value of coil's parameter that maximizes L_s and minimizes R_s simultaneously.
- The optimization is now rewritten as:

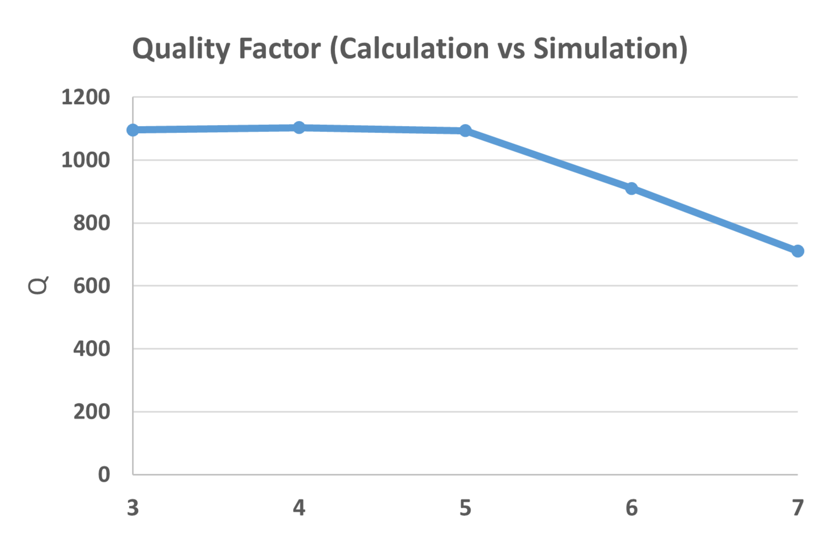
$$\max Q(r_{i0}, r_{o0}, C, n)$$
$$\text{s.t.} \begin{cases} r_{i0}, r_{o0}, C > 0, & n > 2, \\ r_{o0} > r_{i0}, & 2r_{o0} + \pi C(4n-1) \le S, \\ r_{o0} - r_{i0} \le p \le 1.5(r_{o0} - r_{i0}), & 2\pi f L_s = \frac{1}{2\pi f C_s}. \end{cases}$$

S = coil's maximum outer dimeter

Simulation



L_s and R_s of the Coil

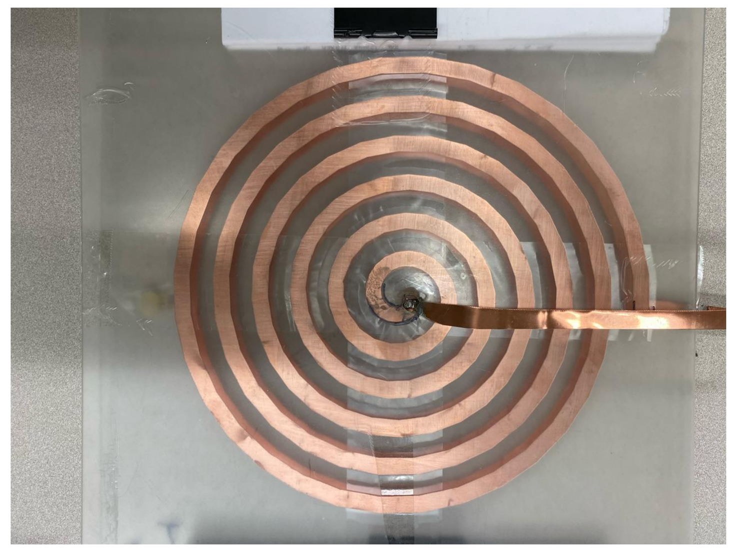


Q-factor of the Coil

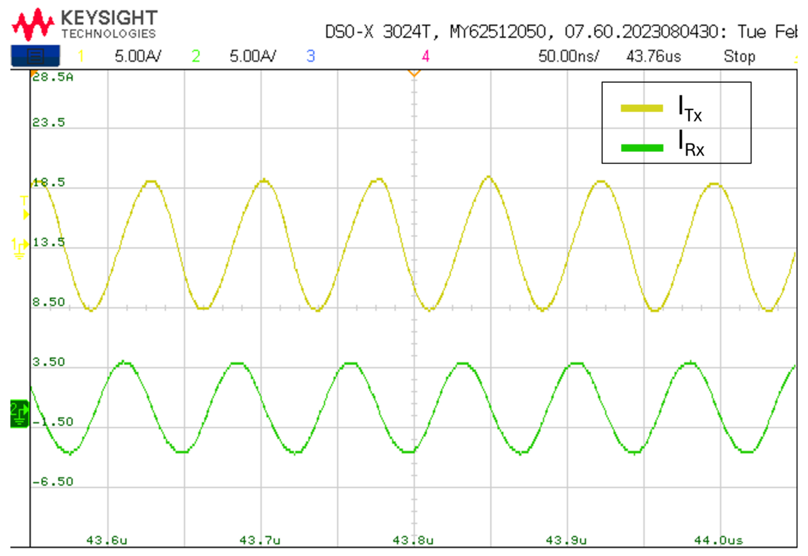
- Ansys HFSS is used to simulate the coil's parameter obtained from the optimization at operating frequency f=13.56 MHz and copper thickness t=0.5 mm.
- Air is selected as the dielectric for easier fabrication and assembly.
- The result showed that there is a good agreement between calculation with the simulation.
- Coil with number of turn n=6 is selected since it gives high quality factor (910) with high inductance (3.2 μH).

Coil Fabrication and Testing

- The coil is fabricated from a square copper sheet with side S.
- Water jet is used to reduce the cost of coil's production.



Fabricated Coil



Tx and Rx Current

- The coil's parameters are measured using a Keysight network analyzer (E5601B).
- The measured value of the Tx coil are $L = 3.5\mu H, Rs = 0.4\Omega$, and $Q = 745$.
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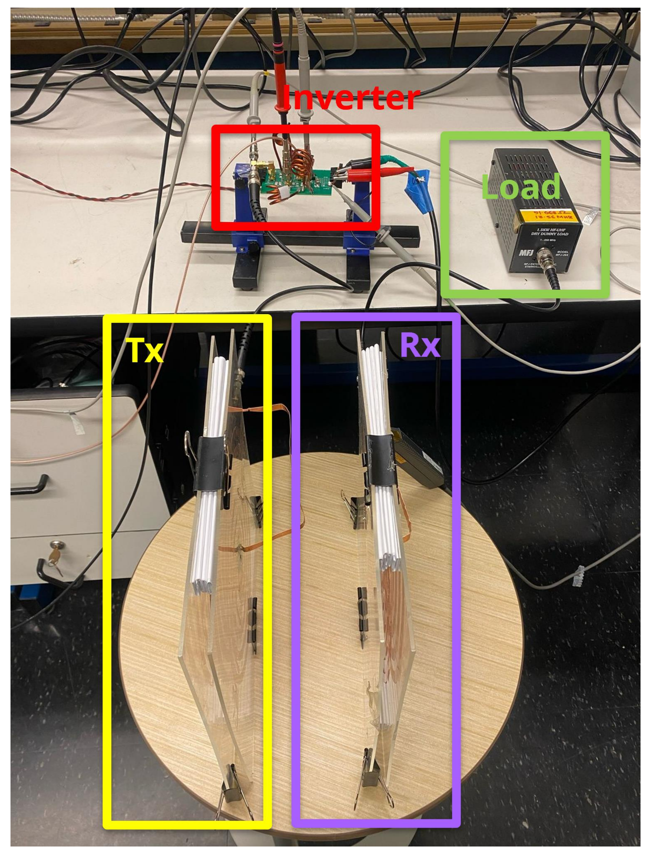
- The experimental value showed deviation from calculation and simulation.
- This is largely contributed to challenges in measuring coil's parameter at high frequency
- The performance of the coil is confirmed by testing it with a class Φ2 inverter.
- The experimentation shows that the coil is able to transmit 400 W power over a 12.2 cm distance with the efficiency of 96%



Experimental Setup

Future Work, References, and Acknowledgments

- Further improvements to coil's measurement method
- Investigation on the optimization's convexity
- Testing the coils using DC-DC converter

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[1] J. Li and D. Costinett, "Analysis and design of a series self-resonant coil for wireless power transfer," in 2018 IEEE AppliedPower Electronics Conference and Exposition (APEC), San Antonio, TX, USA, 2018, pp. 1052–1059.
[2] S. S. Mohan, M. del Mar Hershenson, S. P. Boyd, and T. H. Lee, "Simple accurate expressions for planar spiral inductances,"IEEE Journal of Solid-State Circuits, vol. 34, no. 10, pp. 1419–1424, 1999.
[3] V. Leus and D. Elata, "Fringing field effect in electrostatic actuators," 2004.

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