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High Q Self-Resonant Structures for Wireless Power Transfer

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Motivation

- Range and efficiency of wireless power transfer (WPT)
  - Impacts user experience
  - Limits the number of applications
- Theoretical maximum efficiency is $\eta_{max} = \frac{(Qk)^2}{\left(1+\sqrt{1+(Qk)^2}\right)^2}$.
  - The magnetic coupling factor (k) decreases at long range
  - The quality factor (Q) of the resonant coils is a key metric for increasing range and efficiency.
- **Increase the range and efficiency of WPT by increasing the quality factor of the resonant coils**
  - **Without increasing the size of the coils**

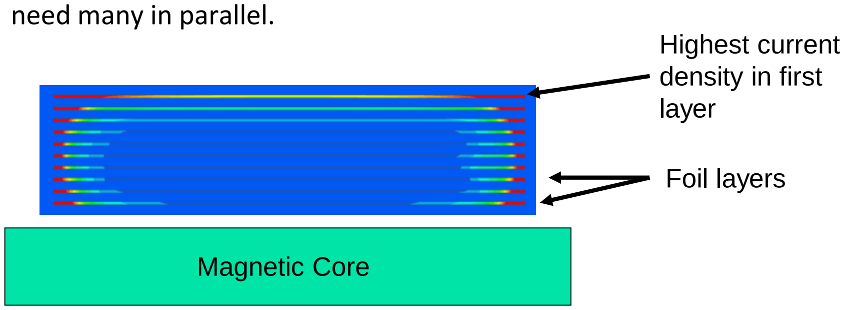
Limitations of conventional wireless coils

- Dominant loss is typically in the conductor
- Solid magnet wire:
  - Skin effect → most of conductor is not utilized
- Litz wire:
  - Twisting forces equal current sharing → good conductor utilization
  - Difficult to terminate → increased loss
  - Proximity effect → severe losses if strand diameter (d_s) is not very small
    - Strand diameters $< 2\delta$ is not an adequate design rule
    - AC resistance factor is given by* $\frac{R_{ac}}{R_{dc}} = 1 + \frac{(\pi\, n\, N)^2 d_s^6}{192\delta^4 b^2}$
    - Small strand diameters are expensive and are limited to ~32 µm (48 AWG)

*Sullivan, Charles R., and Richard Y. Zhang. "Simplified design method for litz wire." Applied Power Electronics Conference and Exposition (APEC), IEEE, 2014.

Thin foil layers

- Easy to get thickness << skin depth
  - Commercially available
  - Inexpensive
  - Freestanding foil down to ~ 6 µm
- Thin layers have high dc resistance—need many in parallel.



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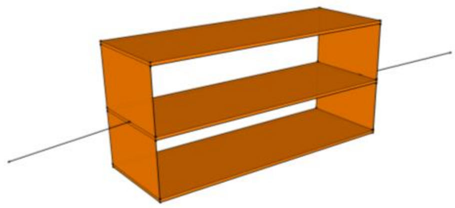
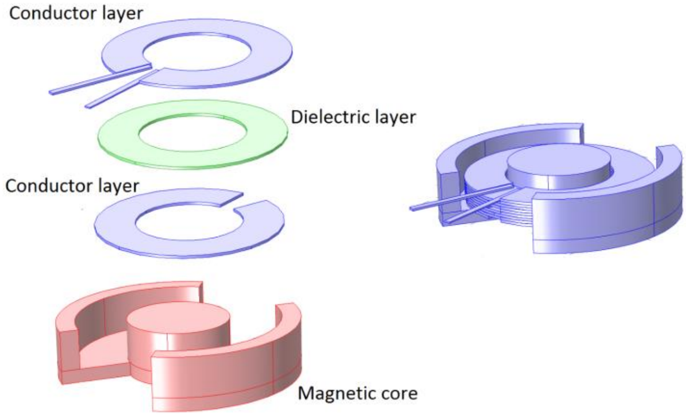
Equal current sharing through capacitive ballasting



- Use capacitance between layers to accomplish two things:
  - Force equal current sharing between layers
  - Provide resonant capacitance

How to implement these concepts?

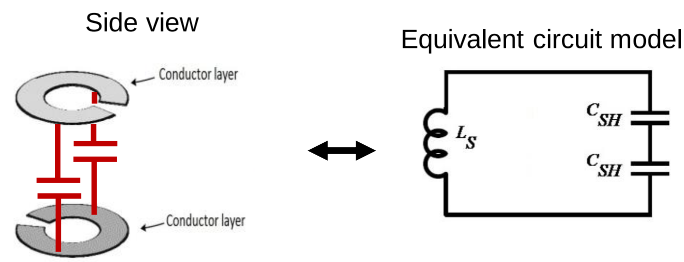
Self-resonant multi-layer structure*



* Patent Pending

Operation principle – single section

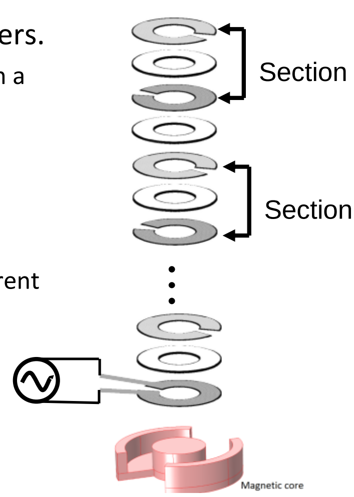
- Each section:



- Inductive current loop
- Capacitive connection between foil layers through dielectric

Operation principle – many sections

- Strong mutual coupling between all layers.
  - Each section capacitance is coupled to form a parallel LC resonator
  - Coupled section capacitance forces equal current sharing in each layer
  - Integrated capacitance eliminates high current terminations



Self-resonant multi-layer structure*

- Benefits similar to litz wire
  - Good conductor utilization due to equal current sharing between many thin layers
- Overcomes issues associated with litz wire
  - Thin foil layers mitigate loss due to proximity effect
  - Integrated capacitance eliminates high-loss terminations

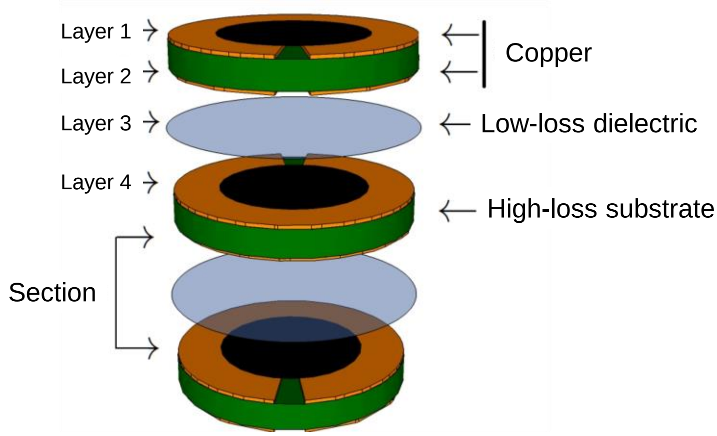
* Patent Pending

The challenge

- High-Q → thin foil layers (5-15 µm) which are difficult to handle
  1. Copper laminated low-loss substrates
     - Low-loss relative to FR4/polyimide but not PTFE
     - Available materials are expensive
  2. Copper laminated high-loss PCB substrates (FR4/polyimide)
     - Available materials are inexpensive
     - High-loss makes this method not feasible

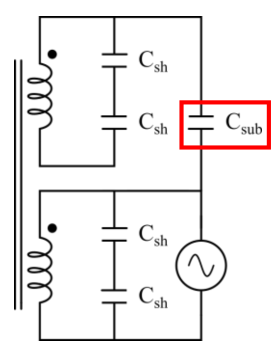
- Contribution of this paper: Develop a structure that incorporates the high-loss substrate into the self-resonant structure in order to handle thin foil layers without adversely impacting the Q.

Modified self-resonant structure



Modified self-resonant structure

- The capacitance in the substrate C_{sub} is not excited during resonance
- Thickness, dissipation factor, and dielectric constant of substrate do not impact the resonance
- Therefore we can use a high-loss substrate to support thin foil layers without impacting Q



Loss modeling

- Loss models are used to create a design space (details in paper)
  - The winding resistance

$$R_{wind} = \frac{R_{LF}}{m} F_r$$

← ac resistance factor

  - ESR modeling dielectric loss

$$R_{dieletric} = \frac{2D_d}{mC_{sh}\,\omega}$$

← dielectric dissipation factor

  - ESR modeling core loss

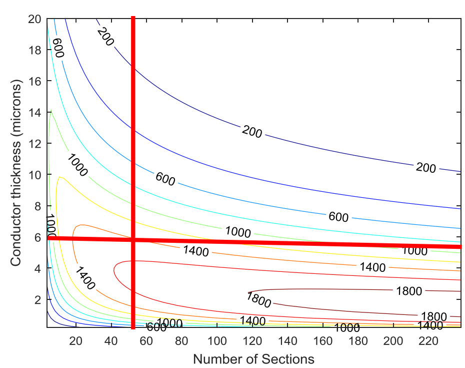
$$R_{core} = \mathbb{R}(j\omega L^*), \text{ where } L^* = \frac{1}{\mathcal{R}_c^* + \mathcal{R}_a}$$

← complex core reluctance

Prototype design space

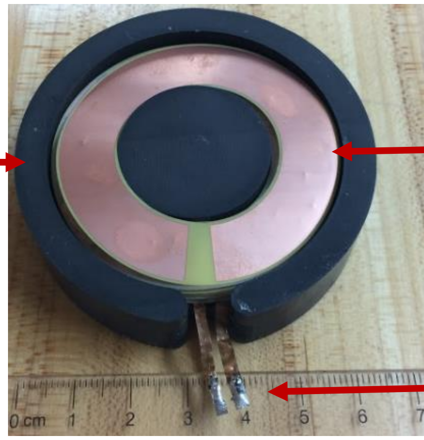
- 6.6 cm pot core made from Fair-Rite 67 material
- 48 sections
- 6 µm copper*
- 25 µm polyimide*
- 25 µm PTFE dielectric*

6.78 MHz Structure Design Space



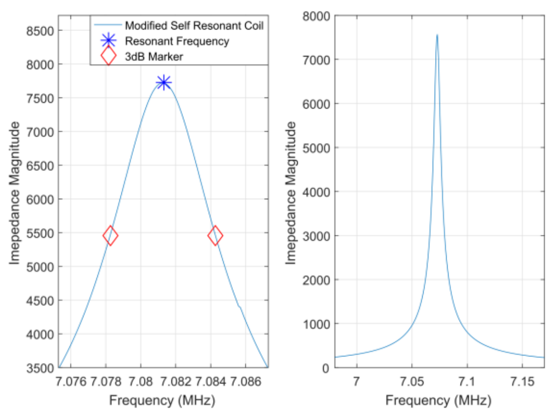
* Selected based on availability and ease of handling

Prototype



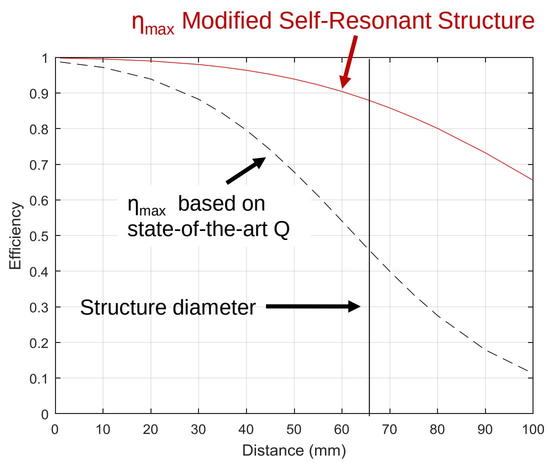
Experimental data

- Q = 1177
- Diameter (D) = 6.6 cm
- $Q_d = \frac{Q}{D} = 178\ \text{cm}^{-1}$
- Q_d is > 6x larger than that of litz designs in the literature
- Matches within 15% of theory.



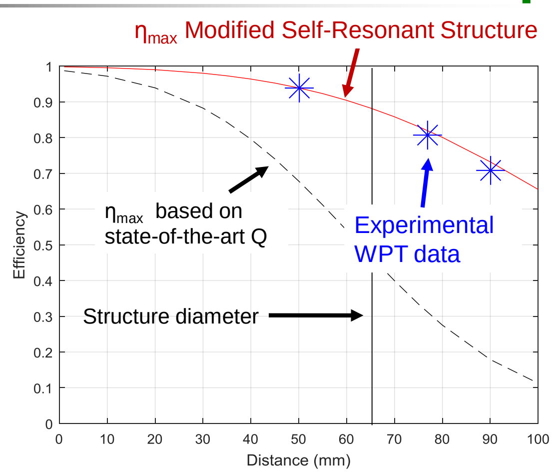
Wireless power transfer efficiency versus distance

- $\eta_{max} = \frac{(Qk)^2}{\left(1+\sqrt{1+(Qk)^2}\right)^2}$
- Modified Self-Resonant Structure
  - Experimental Q
  - k from FEA of magnetic core
- Baseline for comparison
  - State-of-the-art Q from literature
  - Same magnetic core

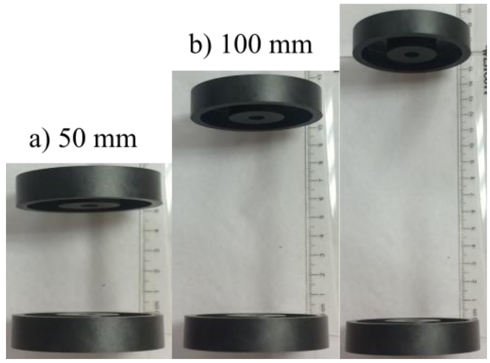


Wireless power transfer efficiency versus distance

- Experimentally validated wireless power transfer between two modified self-resonant structures
- 2x range with η > 94%
- η > 80% at 7.5 cm
- η > 70% at 9 cm



Performance comparison



New Structure (η%)	94%	65%	25%
State-of-the-art (η%)	67%	11%	2%

Conclusion

- Increase the range and efficiency of WPT by decreasing the energy dissipated in the resonant coils
- The self-resonant structure accomplishes this, but the thin foil layers are difficult to handle
- Modified self-resonant structure
  - Allows thin foil layers to be laminated on high-loss but low-cost substrates
  - High-loss substrates does not contribute to loss
  - Experimental Q is 1177 despite structure diameter of 6.6 cm
    - 6x improvement over state-of-the-art
  - Experimental wireless power transfer setup
    - 2x range with η > 94%
- Multilayer self-resonant structures can also be used for resonant power conversion (paper ID 1669)