Layered DD Coil: An improved coil structure for inductive wireless power transfer

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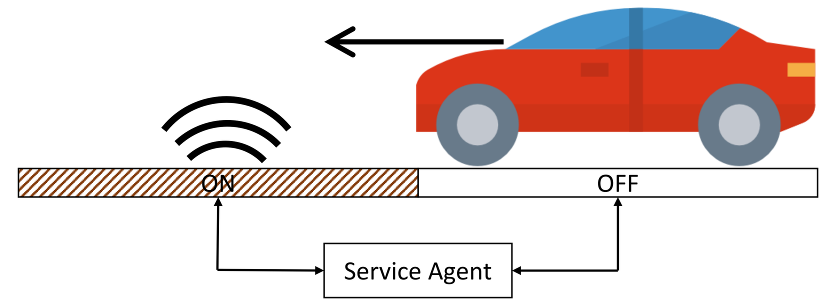


Objectives

- Implement Layered DD coil
- Compare against other coil structure
- Implement magnetic field shielding

Introduction

Wireless power transfer (WPT) has gained lots of attention and recognition in smaller consumer electronics.

Figure 1: Application of WPT

Challenges:
- Amount of power transmitted over a long distance
- Exposure of living organisms around

Proposed Solution:
- Construe the field to add-up constructively
- Shield the field

Shielding
Involves providing an alternate path for magnetic field to pass through thereby protecting the intended object or region. Typically done by using a magnetic material with high permeability.

Magnetic Field line constructive adding up
Is achieved by the use of coil structures that provide more constructive interaction between the magnetic flux lines. Various coil structures have been use din literature which include: circular, square, helical and Double D [2].

Novelty
A novel Layered DD coil is presented in this project. The coils on the layers are oriented such that the individual mutual inductance add up to improve the overall inductance of the coil.

Methodology

Figure shows the method adopted in actualizing this project. ANSYS Maxwell software package was used for modeling the coil. It is based on Finite Element Analysis (FEA) method.

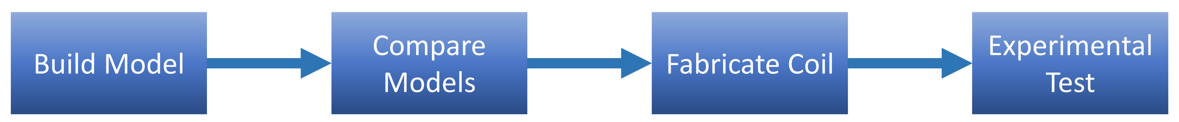


Figure 2: Block diagram for this research showing key steps adopted in its actualization

- Modeled coil structure is tested using various parameters. These include:
  - Shielding materials
  - Amount of power
  - Efficiency
- Various coil structures from literature are modeled and tested alongside the layered DD **(novelty)**
- A prototype of the best performing coils are then built and tested for further testing
- The plate was 3D printed using PLA
- 14 AWG litz wire was used to mitigate the eddy current effect
- Function generator (3312OA), oscilloscope (Tektronix THS3014) and a power amplifier (E&I 1020L) were used for the exciting and taking measurement of the coils

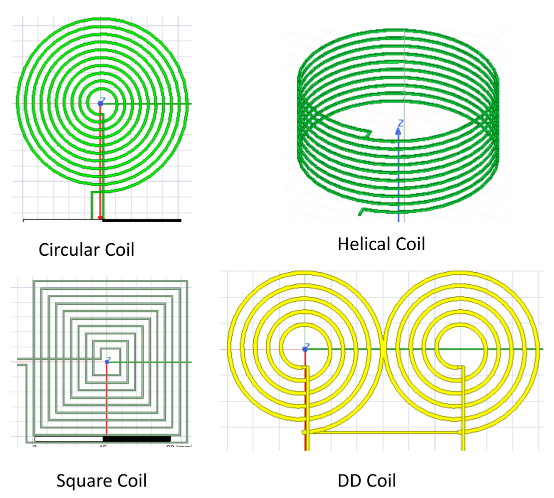
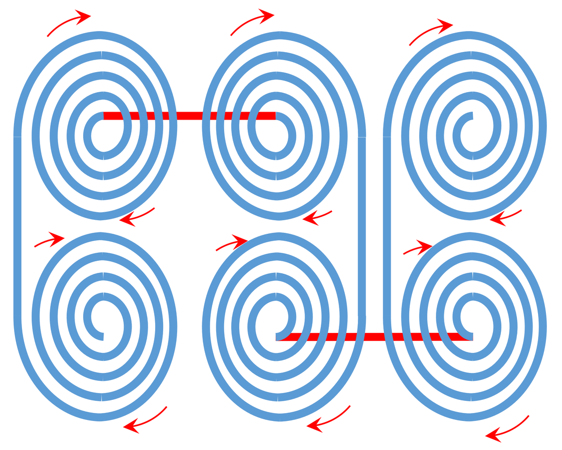


Figure 3: Top performing coils compared [1]

Modeling

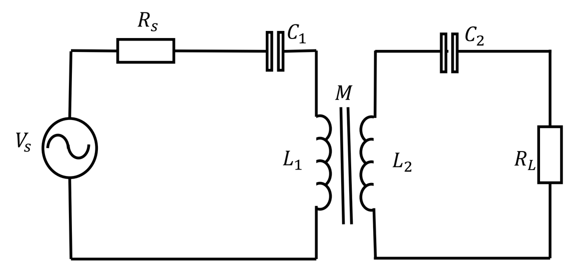


- Current direction ensures that the generated magnetic field adds up constructively thereby an increase in inductance.
- Each layer has an inductance specified by the equation

Figure 4: Schematic of Proposed Layered DD coil

$$L_{DD} = L_{left} + L_{Right} - 2M \quad (1)$$

Efficiency of Power Transfer [1]



$$\eta = \frac{-\omega_s^2 k^2 L_1 L_2}{R_l R_s + \omega_s^2 k^2 L_l L_s} \quad (2)$$

Where ω is operating frequency, k coupling coefficient, L_1, L_2 inductance of coils 1 and 2, R_s, R_l source and load resistance.

Figure 5: Resonant WPT circuit diagram

Inductance Matrix

$$L_{LDDmat} = \begin{bmatrix} L_{11} & M_{12} & M_{13} \\ M_{21} & L_{22} & M_{23} \\ M_{31} & M_{32} & L_{33} \end{bmatrix} \quad (3)$$

This shows the interaction between the coil layers. L is the self inductance for the specified layer while M is the mutual inductance between the layers specified. Subscripts represent the layers involved in the interaction.

Simulation and Experiment

Simulation Model

Figure 6: (L-R) DD and LDD coil model

Simulation Model

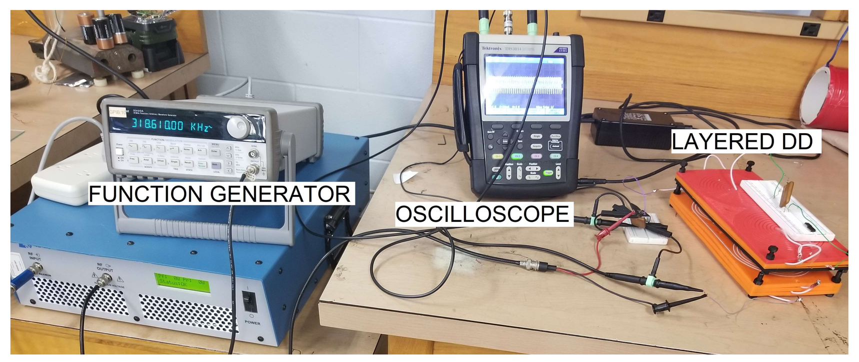


Figure 7: Top performing coils used for comparison

- **Shielding materials:** Ferrite, Neodymium, Nickel, Nickel-Iron, Steel and Cobalt-Iron.
- **Wire Type:** Litz wire
- **Number of turns:** 10

Inductance

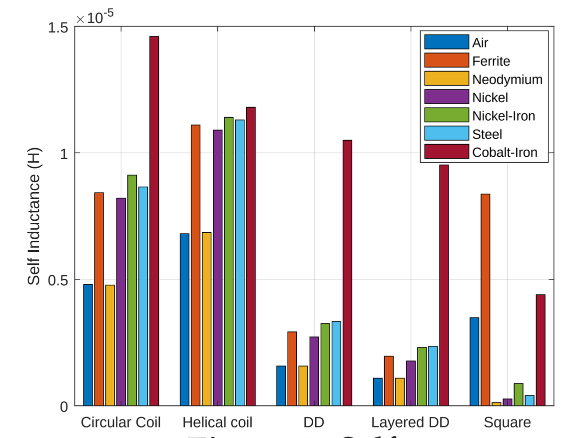


Figure 8: Self

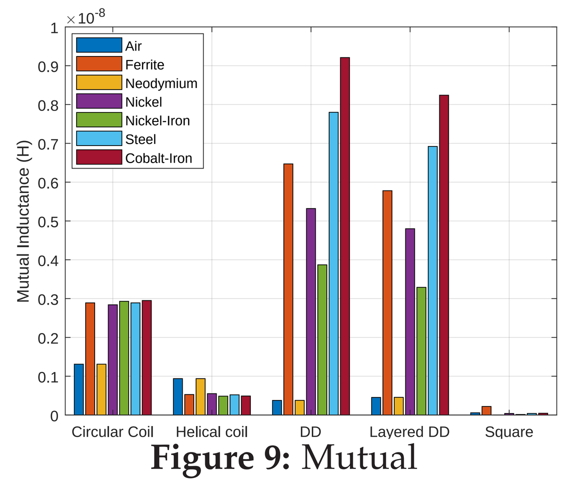


Figure 9: Mutual

LDD coil gives a higher self and mutual inductance and values this leads to better power transfer performance.

Power Transfer

Table 1: Tranmit power

Material	g(mm)	$P_{DD}(W)$	$P_{LDD}(W)$
Air	15.24	4.69×10^{-3}	7.49×10^{-3}
Air	40.64	9.21×10^{-4}	8.58×10^{-3}
FE1	15.24	4.74×10^{-3}	7.47×10^{-3}
FE1	40.64	8.05×10^{-4}	5.28×10^{-3}
FE2	15.24	5.10×10^{-3}	8.12×10^{-3}
FE2	40.64	1.06×10^{-3}	5.55×10^{-3}
AL1	15.24	1.02×10^{-3}	5.78×10^{-3}
AL1	40.64	1.33×10^{-4}	1.81×10^{-3}
AL2	15.24	3.57×10^{-4}	4.30×10^{-3}
AL2	40.64	3.04×10^{-5}	5.23×10^{-4}

- Comparing LDD and DD coils power transfer at air gaps of 15 and 20 mm
- LDD transmitting more power than DD
- Ferrite shield gives more power transfer than other shielding materials

Efficiency

Table 2: At resonance

Material	g(mm)	$Eff_{DD}(\%)$	$Eff_{LDD}(\%)$
Air	15.24	71.05	78.26
Air	40.64	19.63	68.89
FE1	15.24	69.77	92.16
FE1	40.64	29.18	91.84
FE2	15.24	25.53	73.96
FE2	40.64	30.16	70.12
AL1	15.24	31.12	79.05
AL1	40.64	4.42	25.84
AL2	15.24	14.34	42.64
AL2	40.64	0.73	10.75

Table 3: Maximum Power

Material	g(mm)	$Eff_{DD}(\%)$	$Eff_{LDD}(\%)$
Air	15.24	61.80	91.1
Air	40.64	47.07	93.56
FE1	15.24	81.13	92.16
FE1	40.64	34.33	91.84
FE2	15.24	88.29	73.96
FE2	40.64	49.23	74.23
AL1	15.24	31.12	99.99
AL1	40.64	4.42	27.18
AL2	15.24	14.34	51.51
AL2	40.64	0.732	10.75

Shielding

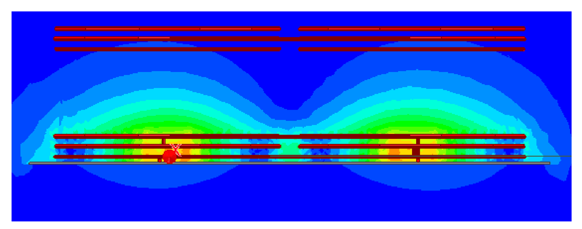


Figure 10: Ferrite Shield on trasmitter only

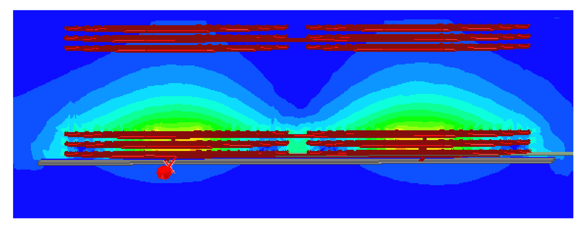


Figure 11: Ferrite Shield on both sides

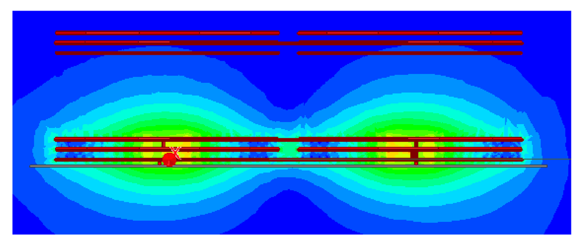


Figure 12: Aluminum Shield on trasmitter only

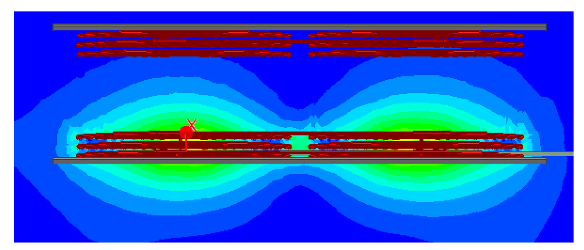


Figure 13: Aluminum Shield on both sides

Magnetic Flux lines

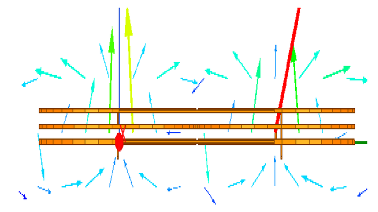


Figure 14: Front View

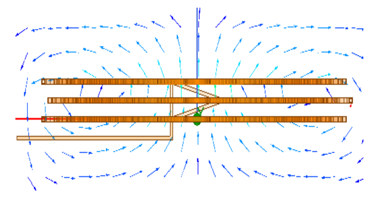


Figure 15: Side View

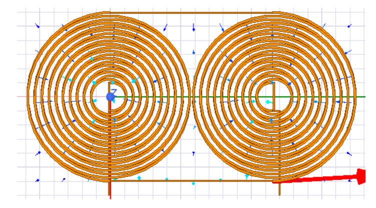


Figure 16: Top View

- See how the magnteic flux lines is distributed around the coil adding up constructively.

Discussion and Contribution

1. The novel means by which the coil constructively combines the magnetic field leads to an increase in the overall magnetic field density around the coil. This translates to more inductance and power storage **(self-inductance)** and sharing capability **(mutual-inductance)**.
2. Equation (2) shows a direct relationship between the mutual inductance and transfer efficiency. This explains why LDD has a better power transfer. It exhibited significant amount of inductance than the DD **(See results in Inductance)**.
3. Ferrite exhibits the most significant shielding and it has the most magnetic permeability
4. Both DD and LDD have similar structure, however, a much wider ground area is required for DD to achieve similar inductance as LDD.
5. This increase is not always feasible since there is usually a limitation of size.

Conclusion

- Layered DD coil performed more efficiently that other coil types
- Using Ferrite on the transmitting side only performed almost as good as when on both sides
- Potential for saving on material usage when Ferrite is used on only the transmitting side

Future Research

Implementation of Magnetic Beamforming using
- LDD coils
- various optimization algorithm.

These are intended to operate in a dynamic wireless power transfer situation.

Acknowledgment

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References

[1] Muhammad Enagi Bima, Indranil Bhattacharya, and Syed Rafay Hasan. Comparative Analysis of Magnetic Materials, Coil Structures and Shielding Materials for Efficient Wireless Power Transfer. In *2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC+SIPI)*. IEEE, July 2019.

[2] Sadeque Reza Khan, Sumanth Kumar Pavuluri, and Marc P. Y. Desmulliez. Accurate Modeling of Coil Inductance for Near-Field Wireless Power Transfer. *IEEE Transactions on Microwave Theory and Techniques*, pages 1–12, 2018.