Novel Metamaterial Design and AI-based Estimation of Coil Parameters for Efficient Wireless Power Transfer

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OBJECTIVES

- Implement a novel metamaterial (Ferrite-core) based wireless power transfer (WPT) system.
- Estimate optimal metamaterial (MM) size for Improved WPT performance (power received and power transmission efficiency, PTE).
- Develop AI-based algorithms to improve the amount of power received and PTE

INTRODUCTION

Wireless Power Transfer (WPT) has become a focal point of numerous research interests and power transmission in consumer electronics [1, 3] and industrial applications [2].

Figure 1: Common Application of WPT

Limitations:

- Poor Performance over a wide transfer range
- Carries with it the risk of exposure to high frequency electromagnetic radiation

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.

Proposed Solution:

- Use a negative refractive index material to increase the field density and converge the flux line, directionally.
- Shield the field

Performance Enhancement with Meta-material

A notable property of meta-materials is negative refractive index. This is responsible for its inherently negative effective permeability and evanescent wave amplification. While the latter accounts for the increase in magnetic field within the vicinity of the MM Ferrite-core, the former is responsible for the directional channeling and coupling of the flux lines at the receiving coil

Main Contribution

Specifically, the main contribution of this work is design of novel MM Ferrite-core based WPT model and AI-based algorithm for enhanced WPT performance. The design demonstrates optimal performance with small inner and outer core radii compared to large radii, suggesting a potential cost saving in model fabrication.

METHODOLOGY

Fig. 2 denotes the sequencial steps to research implementation. ANSYS Maxwell EDT was used for the coil modeling. It is based on Finite Element Analysis (FEA) method.

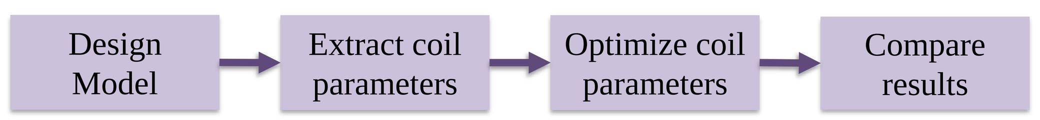

Figure 2: Sequencial Approach to Research Implementation

Metamaterial type:

- Ferrite, Steel, Nickel, Cobalt-Iron, Ni-Fe

Wire Features/Properties:

- Type:Litz,5mm width
- Number of turns: 10

SYSTEM MODELING

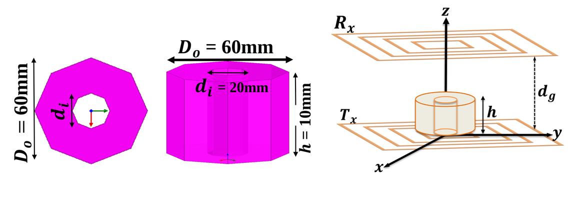

Figure 3: Schematic of Proposed MM Ferrite core with rectangular coil

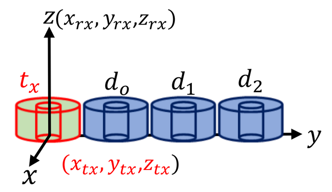

Figure 4: Modeling of Coil Misalignment. d_o,d_1,d_2 denote 25%, 50% and 75% coil-MM misalignment, respectively

- Negative refractive index enhances high effective permeability of the MM Ferrite-core [1].
- Evanescent wave property of the MM engenders amplification of the magnetic field due to the transmitter, straightens the field pattern and converges the flux lines at the receiver
- Improved power and efficiency.

Efficiency of Power Transfer

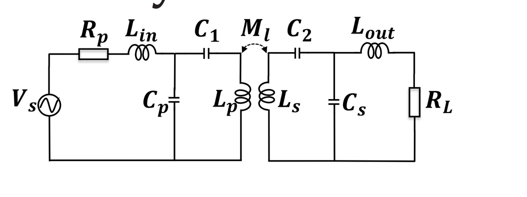

Figure 5: Resonant LCCL WPT circuit diagram

$$L_m = \frac{N\mu}{I}\int \vec{H}.dA \quad (2)$$

$$L_{TX-TX} = L_{tx-tx} + L_m \quad (3)$$

$$\%\frac{P_{out}}{P_{in}} = \frac{-\omega_s^2 k^2 L_p L_s}{R_L R_p + \omega_s^2 k^2 L_p L_s} \quad (1)$$

Where ω_s is the operating frequency, k coupling coefficient, L_p, L_s inductance of coils 1 and 2, R_p, R_L source and load resistance.

The expressions (2) and (3) denote the model equation of L_m, A is the evanescent inductance and surface area of the meta-material respectively, H is the magnetic field strength. Subscripts represent the layers involved in the interaction.

MODEL SIMULATION

Simulation Model

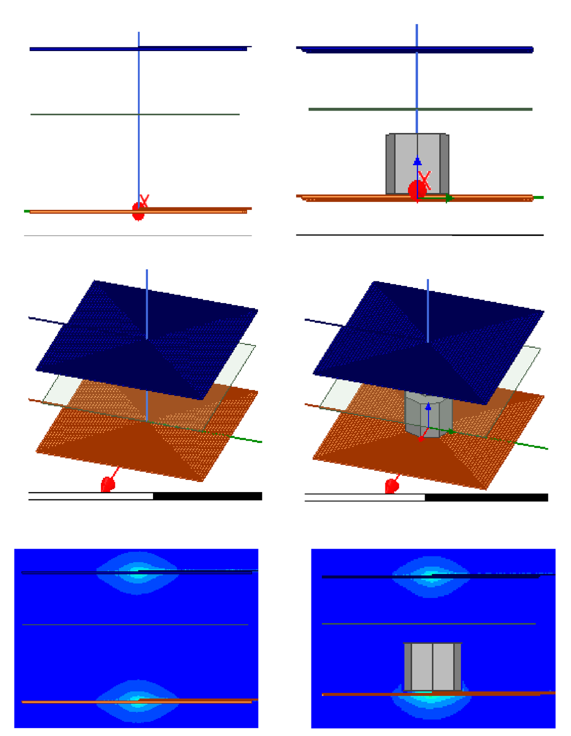

Figure 6: ANSYS based model with (right) and without (left) MM Ferrite core. Top- Front View, Middle- Side View) Bottom- Distribution of H-field

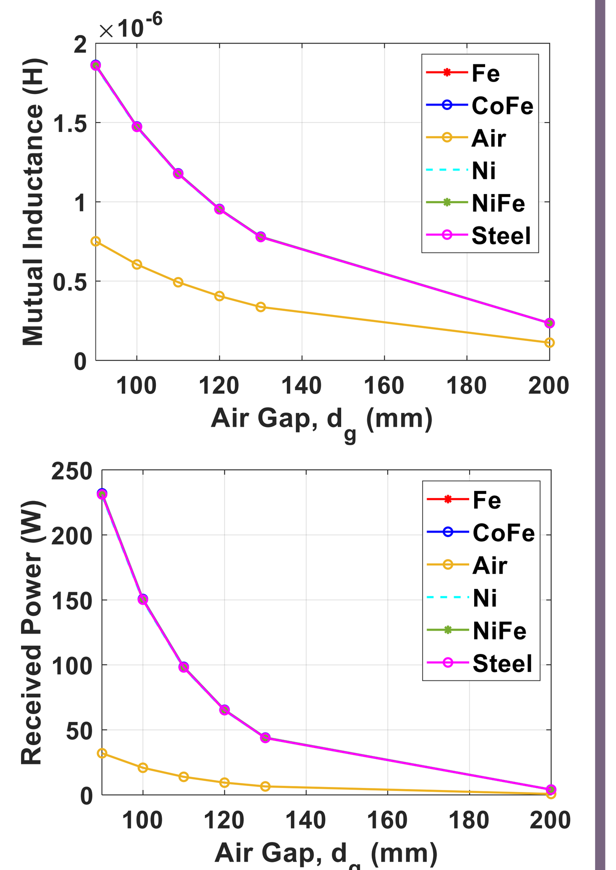

Figure 7: Inductance (top) & Power (bottom) Comparsion for Different Magnetic Materials

INDUCTANCE

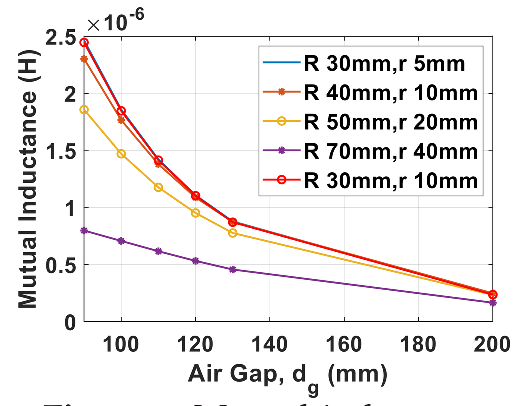

Figure 8: Mutual-inductance

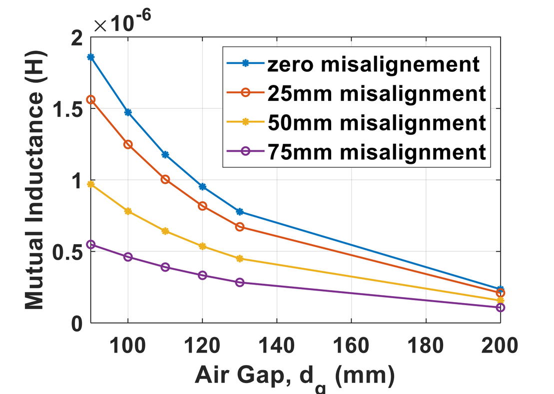

Figure 9: Mutual inductance

Smaller core radius and surface area result in higher mutual inductance, suggesting potential cost saving benefits. Also, mutual inductance decays with increase in Tx-coil - Ferrite-core misalignment

RECEIVED POWER

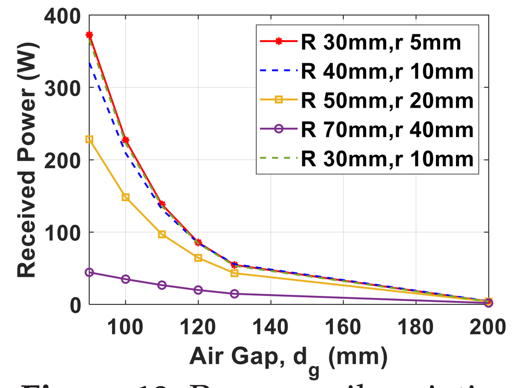

Figure 10: Power- coil variation

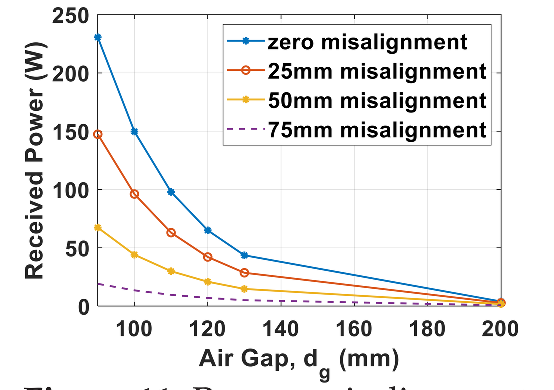

Figure 11: Power- misalignment

- Power and Mutual inductance have a direct relationship, the mutual inductance being a measure of the power stored in the magnetic coil.
- core radius bears a similar effect on the received power as the inductance .
- Small core radius generates high amount of power at the receiving coil

- In simple terms, the slightest displacement between the metamaterial and transmitting coil results in power loss and fluctuating output.
- Divergence of magnetic flux due to cancelatrion pf evanescent property of the Ferrite core.Optimal WPT performance occurs at perfect alignment

EFFICIENCY

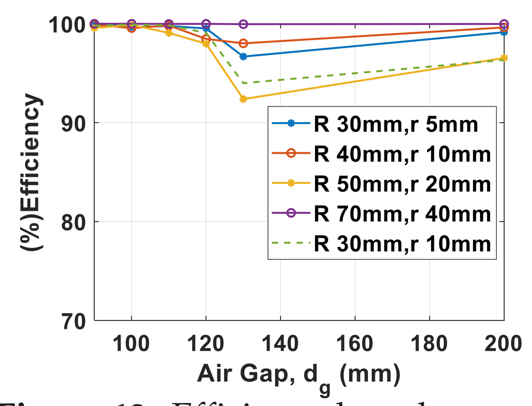

Figure 12: Efficiency-based on core Radii

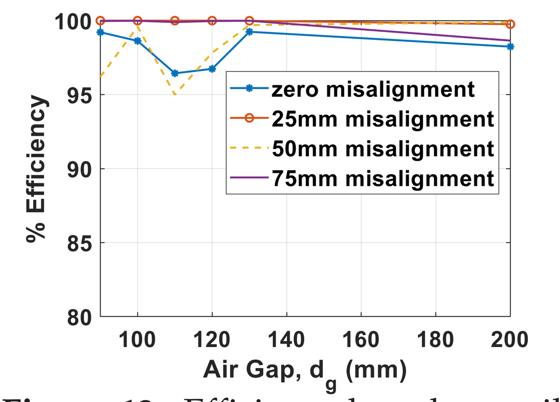

Figure 13: Efficiency-based on coil Misalignment

PERFORMANCE COMPARISON

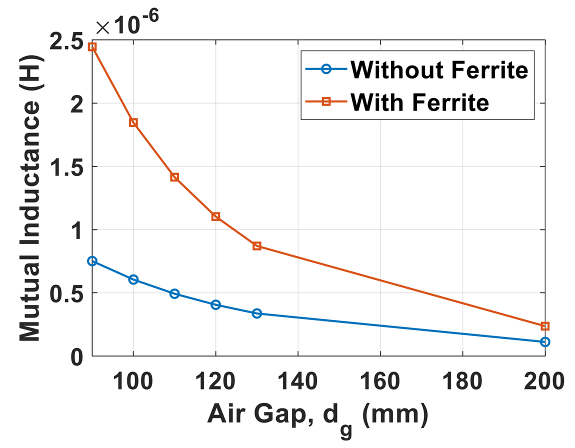

Figure 14: Mutual Inductance-With and Without MM

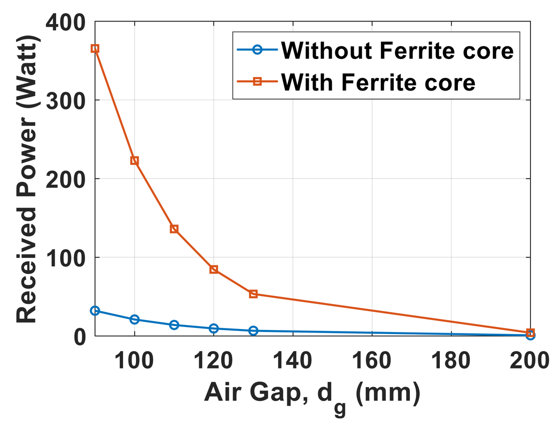

Figure 15: Transfer Power-With and Without MM

ACKNOWLEDGMENT

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MAGNETIC FLUX LINES

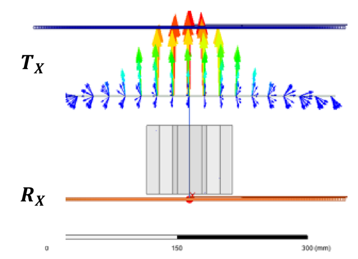

Figure 16: Front view of model showing directional travel of H-field

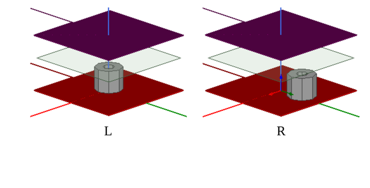

Figure 17: Diametric View of the WPT Design With (R) and Without (L) Misalignment

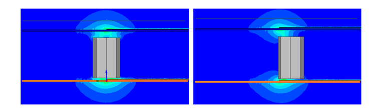

Figure 18: Magnetic-Field Distribution for Perfect Alignment (L) & 75% Misalignment (R)

Fig.16 shows MM enhancing a uni-directional travel and coupling of the flux line towards the Rx-coil.

DISCUSSION OF RESULTS

- Novel metamaterial infused magnetic coil demonstrates higher mutual inductance, transfer power, and power transfer efficiency than other magnetic coils
- Its inherent evanescent wave increases the magnetic field density due to the transmitting coil, straightens the flux lines and enhances a coupling of the same at the receiving coil.
- High magnetic field density corresponds to increased mutual inductance, and power sharing. This explains why the MM has better WPT performance than rectangular coil.
- Misalignment between MM and magnetic coil affects the mutual inductance and transfer power.High misalignment translates to low mutual inductance and power sharing.
- Nearly 100% matching of Matlab and Lt-spice simulation result. This effectively validates the accuracy of the AI-based optimization algorithm.

CONCLUSION

- Significantly high mutual inductance and transfer power had been achieved with MM based WPT compared to coil design
- High mutual inductance, transfer power and efficiency with small sample size of MM Ferrite-core brings up the prospect of cost savings in material fabrication
- Using Ferrite on the transmitting side only, performed almost as good as when on both sides
- Improved WPT model performance (received power and transmission efficiency) with AI-based algorithm

FUTURE RESEARCH

Prototype implementation of dynamic wireless charging of EV based on

- Metamaterial infused LDD coil
- AI-based optimization for improved power.

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

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