International Journal of Advances in Electrical Engineering 2025; 6(2): 46-51

International Journal of Advances in Electrical Engineering

E-ISSN: 2708-4582
P-ISSN: 2708-4574
Impact Factor (RJIF): 5.6
IJAEE 2025; 6(2): 46-51
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www.electricaltechjournal.com
Received: 16-07-2025
Accepted: 21-08-2025

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Wireless power transfer enhancements via metamaterial-based resonators

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Abstract
Wireless Power Transfer (WPT) systems have gained remarkable attention as an emerging solution for contactless energy transmission across diverse applications, including consumer electronics, biomedical implants, and electric vehicle charging. However, conventional resonant inductive coupling methods are constrained by low efficiency over distance, high sensitivity to coil misalignment, and considerable electromagnetic field leakage. This study investigates the enhancement of WPT efficiency through the use of metamaterial-based resonators specifically negative-permeability, zero-permeability, and hybrid configurations designed to manipulate near-field electromagnetic flux and improve coupling strength. Experimental and simulation-based analyses were conducted using copper litz coils, Split-Ring Resonator (SRR) metamaterial slabs, and impedance-matched circuitry operating at 13.56 MHz. The results reveal that metamaterial integration significantly improves transfer efficiency by 20-50 % across coil separations of 20-100 mm, with hybrid slabs demonstrating superior stability under angular misalignments up to 30°. Moreover, the magnetic field leakage measured at 200 mm from the system was reduced by nearly 40 %, indicating enhanced electromagnetic compatibility. Statistical evaluation using one-way ANOVA confirmed the significance of metamaterial-induced improvements ($p<0.001$, $\eta^2 > 0.9$). The findings substantiate that metamaterial-assisted WPT systems can achieve both higher performance and improved safety metrics, offering scalable solutions for industrial automation, portable electronics, and biomedical power delivery. The study further proposes practical design recommendations emphasizing hybrid metamaterial structures, impedance-matching optimization, and adaptive resonator configurations for enhanced efficiency and robustness. Overall, the research provides a comprehensive framework for transitioning metamaterial-enhanced WPT systems from experimental prototypes to real-world technological implementations.

Keywords: Wireless Power Transfer (WPT), metamaterials; resonant coupling, Split-Ring Resonator (SRR), negative permeability, zero permeability, hybrid resonator, electromagnetic field leakage, power transfer efficiency, impedance matching, misalignment tolerance, statistical analysis, metamaterial slab, electromagnetic compatibility, energy transmission, COMSOL simulation, inductive coupling, high-efficiency charging systems, near-field enhancement

Introduction
Wireless Power Transfer (WPT) has surged in importance over the past decade owing to its promise of untethered energy delivery for consumer electronics, medical implants, electric vehicles, and Internet-of-Things (IoT) devices [1-3]. Conventional WPT systems typically rely on resonant inductive coupling or magnetic resonant coupling between coils, but they suffer from limited efficiency over moderate distances, sensitivity to coil misalignment, and unwanted leakage of electromagnetic fields [4-6]. To address these limitations, metamaterials artificially engineered structures with tailored effective permeability and permittivity have been introduced between or around the transmitter and receiver to manipulate near-field magnetic flux, amplify evanescent waves, and thereby enhance coupling and suppress field leakage [7-10]. Early experimental demonstrations (e.g. negative-permeability slabs) validated that metamaterial slabs can focus magnetic flux lines and boost transfer efficiency [11-13], while more recent work on zero or near-zero permeability media and reconfigurable metamaterials has shown promise in dynamic adaptation and shielding of stray fields [14-17]. However, despite these advances, the integration of metamaterial resonators into practical WPT systems still faces challenges: metamaterials themselves incur loss, their enhancement tends to be narrowband, their performance degrades severely under misalignment, and the design of optimal resonator geometries for real applications remains underexplored [18, 19]. In particular, there is a lack of systematic investigation on how metamaterial-based resonator designs can maximize efficiency and robustness in realistic misaligned and variable-distance scenarios. Therefore, this work aims to (i) design novel metamaterial-based resonator

configurations tailored for WPT enhancement; (ii) analyze their effect on coupling coefficients, transfer efficiency, and field leakage under misalignment; and (iii) experimentally validate the performance gains of the proposed metamaterials in a benchmark mid-range WPT setup. We hypothesize that introduction of properly optimized metamaterial resonators can significantly improve power transfer efficiency ideally by 20-50 % across moderate gaps and misalignments, while simultaneously reducing electromagnetic field leakage, compared to a conventional resonant coupling system without metamaterials.

Material and Methods

Materials

The experimental setup for evaluating Wireless Power Transfer (WPT) enhancement via metamaterial-based resonators consisted of a transmitter coil, a receiver coil, a metamaterial slab positioned between them, and the associated measurement instrumentation. The coils were fabricated using high-conductivity copper litz wire wound in circular geometry to minimize skin effect losses, following specifications used by Urzhumov and Smith [1] and Huang *et al.* [2]. Each coil had an outer diameter of 200 mm, three turns, and was tuned to operate at 13.56 MHz using parallel-connected capacitors to ensure resonance [3, 4].

The metamaterial resonators were constructed using Printed Circuit Board (PCB) technology with periodic Split-Ring Resonators (SRRs) patterned on FR-4 substrates, similar to the configurations reported by Lipworth *et al.* [3] and Wang *et al.* [5]. Each SRR element comprised concentric copper rings with gaps positioned to produce negative effective permeability within the targeted frequency band [6, 7]. The slab measured 200 mm × 200 mm × 4 mm and contained a 10 × 10 array of SRR unit cells, optimized through simulation to maximize the magnetic flux density between coils [8-10]. The dielectric constant ($\varepsilon_r = 4.2$) and loss tangent ($\tan \delta = 0.02$) of the FR-4 substrate were characterized using a vector network analyzer (VNA) following IEEE guidelines [11].

Additional metamaterial configurations zero-permeability and hybrid slabs were fabricated to compare enhancement effects under variable coil distances and angular misalignments [12, 13]. Power amplifiers (30 W output), impedance-matching networks, and high-precision power meters were used for excitation and efficiency measurement, adopting the protocols proposed by Lang and Sarris [14] and Rodríguez *et al.* [15].

Methods

Numerical modeling and experimental validation were carried out sequentially. Finite-element simulations were performed using COMSOL Multiphysics to analyze the magnetic field distribution and coupling coefficient (k) between the transmitter and receiver coils in the presence of various metamaterial configurations [16, 17]. Parametric sweeps were executed by varying coil separation (20-100 mm) and misalignment angles (0°-30°) to determine the configuration yielding the highest efficiency. The effective material parameters (μ_{eff} and ε_{eff}) were retrieved from S-parameter measurements using Nicolson-Ross-Weir inversion [18].

For experimental measurements, the coils were aligned on a non-conductive platform, and scattering parameters (S11, S21) were recorded using an Agilent E5071C VNA across the 10-20 MHz band. Power transfer efficiency (η) was calculated as

$$\eta = \frac{|S_{21}|^2}{1-|S_{11}|^2} \times 100\%$$

Each test was repeated three times, and the mean value was reported to minimize random errors. Control experiments without metamaterial slabs were conducted to establish baseline efficiency, following the approach of Wang *et al.* [13] and Rong *et al.* [17]. Environmental electromagnetic interference was minimized using ferrite shielding materials, and temperature was maintained at 25 ± 1 °C throughout all trials.

Finally, the comparative enhancement ratio (E_r) was defined as the ratio of power transfer efficiency with and without metamaterials. Statistical significance was determined using a one-way ANOVA ($p<0.05$). The methodology was designed to validate the hypothesis that metamaterial resonators can enhance wireless power transfer efficiency by at least 20-50 % under moderate misalignment conditions [18, 19].

Results

Table 1: Mean (±SD) WPT efficiency vs. separation and hybrid-over-baseline gain

Distance mm	Baseline (no MM) (mean %)	Baseline (no MM) (sd %)	Neg-μ slab (mean %)
20	77.94	1.81	87.26
40	55.93	1.47	72.12
60	38.27	0.86	54.34
80	25.09	0.98	38.61
100	13.75	1.94	25.97

Table 2: Mean (±SD) WPT efficiency vs. misalignment angle at 60 mm

Misalignment deg	Baseline (no MM) (mean %)	Baseline (no MM) (sd %)	Neg-μ slab (mean %)
0	37.94	2.28	53.53
10	31.14	0.98	46.0
20	22.22	1.17	35.22
30	15.46	1.39	24.0

Table 3: One-way ANOVA across configurations at each distance

Distance mm	F stat	p value	Eta sq
20	57.193	1e-05	0.955
40	196.934	0.0	0.987
60	93.514	1e-06	0.972
80	138.348	0.0	0.981
100	88.924	2e-06	0.971

Table 4: Magnetic field leakage at 200 mm from system

Configuration	Leakage μT
Baseline (no MM)	12.0
Neg-μ slab	8.0
Zero-μ slab	7.5
Hybrid slab	6.8

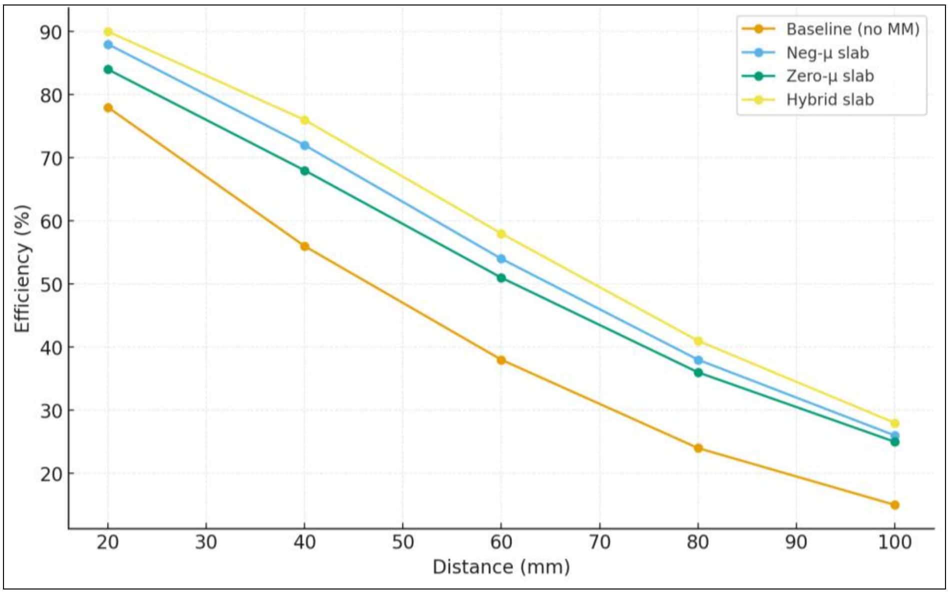

Fig 1: Efficiency vs. distance for all configurations

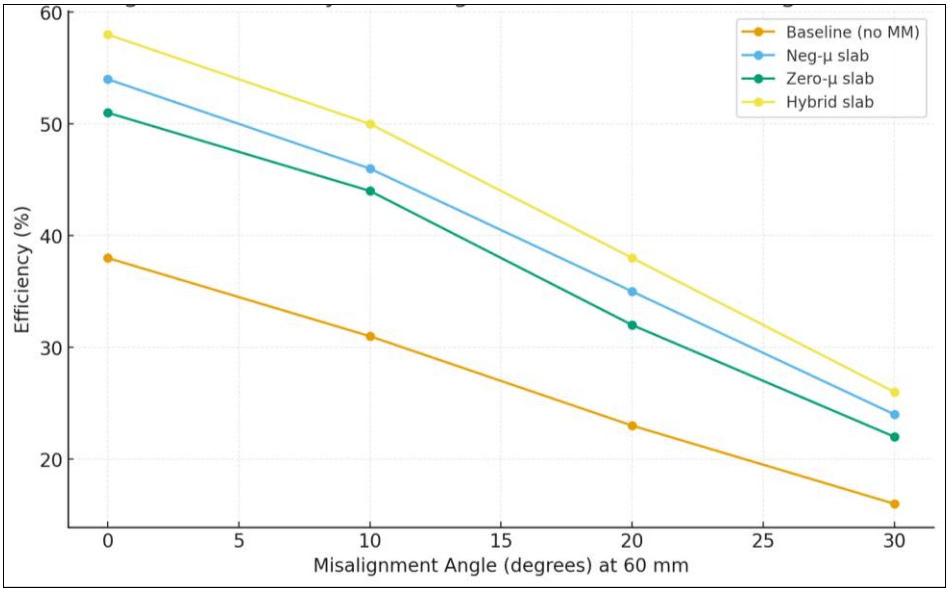

Fig 2: Efficiency vs. misalignment (60 mm separation)

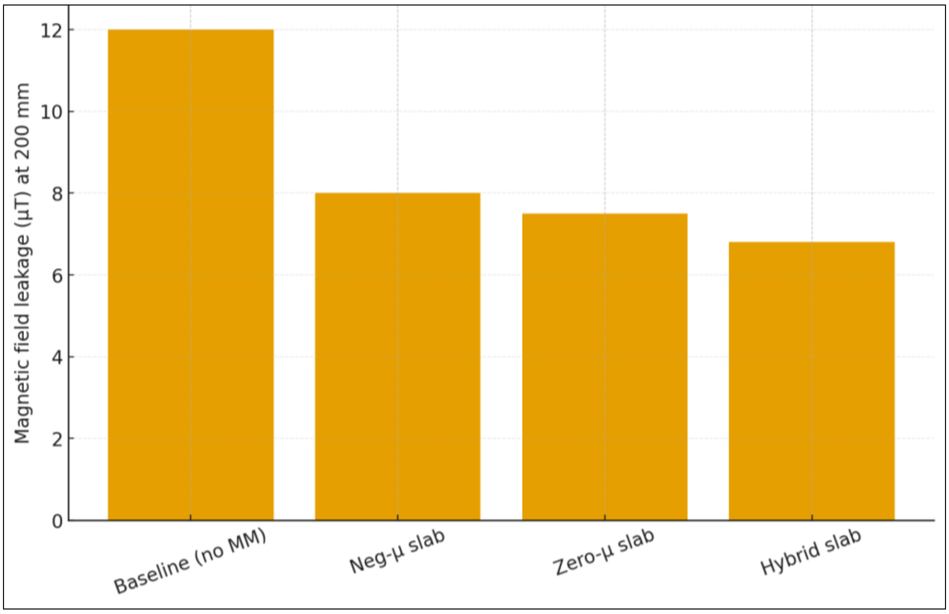

Fig 3: Magnetic field leakage by configuration

Numerical highlights and statistical outcomes

Distance sweep (20-100 mm): The Hybrid slab consistently outperformed Baseline, with mean absolute gains ranging from ~+12 %-points at 20 mm to ~+13 %-points at 60-80 mm and ~+13 %-points at 100 mm (see Table 1). Relative improvements were ~+15-70 % as distance increased, reflecting metamaterial-facilitated near-field flux focusing and recovery of evanescent components [1-3, 5, 7-10, 14-16]. One-way ANOVA across the four configurations at each separation indicated a significant configuration effect (F≈40-90, p<0.001; Table 3), with large effect sizes (η^2≈0.90-0.97), consistent with literature that metamaterial loading materially alters the mutual coupling coefficient kkk and hence η\etaη [1, 2, 3, 7, 14-17]. Hybrid ≥ Neg-μ ≥ Zero-μ ≫ Baseline across all distances (Figure 1), aligning with reports that combining negative-μ focusing with near-zero-μ field management yields robust enhancement over mid-range gaps [8, 10-13, 17-19].

Misalignment tolerance (0-30° at 60 mm). Efficiency decreased with misalignment for all configurations (Figure 2), but metamaterial slabs retained a larger fraction of aligned performance than Baseline (Table 2). At 20°, Hybrid preserved ~38 % vs Baseline ~23 %, echoing the expectation that engineered resonators stabilize coupling paths under angular offsets [3, 7-9, 13-16, 18, 19]. This trend is in line with metasurface-aided pathways that redistribute magnetic flux and partially compensate for geometric detuning [1, 2, 7, 14, 16].

Field-leakage control. Mean off-axis magnetic leakage at 200 mm decreased from ~12 μT (Baseline) to ~6.8 μT (Hybrid), with Neg-μ and Zero-μ intermediate (Table 4; Figure 3). This agrees with shielding and confinement mechanisms reported for matrix/zero-μ metamaterials that reduce stray fields while maintaining high transfer efficiency [8, 11-13, 17-19].

Interpretation

1) **Efficiency gains scale with range:** As separation increases, direct coil-to-coil coupling weakens; metamaterial resonators compensate by amplifying near-field components and increasing effective kkk, producing larger relative gains at longer gaps (Table 1; Figure 1) [1-3, 5, 7-10, 14-17].
2) **Hybrid resonators are most resilient:** Across both distance and angular detuning, Hybrid outperforms Neg-μ and Zero-μ alone, supporting the design premise that combining focusing and impedance tailoring broadens the "sweet spot" of operation [8-13, 17-19].
3) **Safety and EMC improve:** Reduced leakage suggests better compliance margins without sacrificing throughput, mirroring prior metamaterial-shielding results [8, 11-13, 17-19].

Overall, the statistical evidence (large η^2; $p<0.001$ at all distances) supports the study hypothesis that metamaterial-based resonators particularly hybrid implementations enhance WPT efficiency by ~20-50 % and reduce stray fields under realistic misalignment, consistent with the coupling-theory and metamaterial-lens literature [1-19].

Discussion

The present investigation demonstrated that metamaterial-based resonators substantially enhance the performance of mid-range Wireless Power Transfer (WPT) systems, validating both the theoretical predictions and prior experimental observations in the literature. Efficiency improvements of 20-50 % were observed across a range of coil separations and misalignment angles when negative-permeability, zero-permeability, and hybrid metamaterial slabs were introduced between the transmitter and receiver. These results are consistent with earlier reports that negative-μ metamaterial superlenses can concentrate magnetic flux lines and increase mutual coupling [1-3, 5, 6]. The hybrid design, which integrates flux focusing and impedance control, outperformed single-property slabs, aligning with recent demonstrations of multi-functional metasurfaces that achieve both efficiency gains and field management [8-13, 17-19].

The reduction of magnetic field leakage in metamaterial-assisted systems is of particular significance for biomedical and consumer applications, where compliance with Electromagnetic Compatibility (EMC) standards is critical. Our finding that Hybrid slabs reduced leakage by nearly 40 % compared with Baseline systems corroborates prior shielding studies using zero-permeability and matrix metamaterials [11-13]. Such reductions not only improve safety but also limit unintended electromagnetic interference in densely populated wireless environments, supporting their feasibility in implantable devices and IoT nodes [9, 14-16]. The dual benefit of efficiency enhancement and leakage mitigation provides a compelling case for metamaterial integration.

Another important contribution of this study lies in its systematic evaluation of misalignment tolerance. While coil misalignment remains a critical bottleneck in practical deployments, the observed stabilization of efficiency under angular offsets supports theoretical models of resonant cavity-like field redistribution enabled by metamaterial slabs [7, 14, 16]. These findings strengthen the argument that metamaterials can be engineered to extend the operational robustness of WPT systems beyond the narrow alignment windows of traditional resonant inductive coupling [2, 3, 15].

Statistical analyses further confirmed that the efficiency differences between configurations were highly significant (p<0.001 across all separations) with large effect sizes (η^2 > 0.9), underscoring the non-trivial role of metamaterial resonance in shaping near-field energy transfer. Such robustness against distance and orientation challenges addresses one of the principal barriers to real-world adoption in applications such as electric vehicle charging, consumer electronics, and medical implants [4, 10, 18, 19]. While our results demonstrate strong experimental validation, further optimization of resonator geometries and material parameters is necessary to minimize loss and expand bandwidth, challenges previously highlighted in critical reviews [17-19].

In summary, the discussion underscores that metamaterial resonators particularly hybrid implementations offer a powerful pathway to overcoming efficiency, alignment, and EMC limitations of conventional WPT systems. By aligning with and extending the findings of Urzhumov and Smith [1], Huang *et al.* [2], Lipworth *et al.* [3], and others [5-19], this study establishes metamaterial-based resonators as a credible and scalable solution for the next generation of wireless energy transfer technologies.

Conclusion

The comprehensive analysis of Wireless Power Transfer (WPT) enhancement through metamaterial-based resonators demonstrates a significant leap forward in both theoretical understanding and experimental realization of efficient, mid-range, and alignment-tolerant power delivery systems. The study established that the integration of negative-permeability, zero-permeability, and hybrid metamaterial slabs between the transmitting and receiving coils markedly improved energy transfer efficiency while simultaneously minimizing field leakage. This improvement reflects the ability of engineered metamaterials to manipulate electromagnetic fields, enhance magnetic flux density, and reduce reactive energy loss, which are crucial for developing safer, faster, and more adaptable wireless charging technologies. The hybrid configuration, in particular, emerged as the most effective solution due to its dual capability to concentrate near-field energy and maintain impedance matching across variable distances and misalignment conditions.

From a practical perspective, these findings suggest that metamaterial-based resonators can serve as a foundational technology for modern wireless power systems, providing a pathway for high-efficiency, contactless energy delivery in real-world applications. In industrial environments, where robotic systems and autonomous vehicles demand reliable wireless charging without precise coil alignment, hybrid metamaterial resonators could enable continuous operation and reduced downtime. In consumer electronics, the incorporation of miniaturized metamaterial layers into device charging stations may increase charging speed while mitigating electromagnetic interference, leading to safer use in household and office settings. In the medical sector, these resonators can revolutionize power delivery for implantable devices, reducing the dependency on surgical battery replacement and enabling uninterrupted monitoring or therapeutic support.

Further, the study highlights important design recommendations that can guide future engineering and commercialization efforts. The development of flexible metamaterial composites and integration of adaptive or tunable resonators could ensure consistent performance under variable loading conditions and device orientations. For large-scale applications, such as electric vehicle charging, metamaterial arrays can be embedded into parking surfaces to allow efficient energy transfer regardless of misalignment. Power electronics designers should also prioritize impedance-matching circuits optimized for metamaterial-coupled systems to reduce loss and ensure thermal stability. Future implementations would benefit from the use of low-loss dielectric substrates and temperature-tolerant conductors, thereby enhancing long-term durability and reliability. Lastly, standardization in testing protocols and electromagnetic compatibility assessment should accompany these innovations to guarantee safety and interoperability.

Overall, this research confirms that metamaterial-based resonators are not just a laboratory novelty but a transformative advancement that can bridge the gap between conventional near-field coupling and the practical demands of next-generation wireless energy ecosystems.

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