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Optimizing Wireless Power Transfer Efficiency at 13.56 MHz Using Double Negative Metamaterials

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ABSTRACT: Recent advancements and innovations in wireless power transfer (WPT) technology have led to an increased demand for systems with high power transfer efficiency (PTE) and extended transmission distances to meet the needs of end users. However, many existing WPT systems suffer from limited PTE and restricted transmission ranges due to their reliance on inductive coupling. A significant drawback of inductive coupling is the sharp decline in PTE as the distance between the transmitter and receiver coils increases. To address these limitations, this study proposes the design of an inductive WPT system enhanced by the integration of metamaterials (MTMs) to improve PTE through magnetic field manipulation. By strategically positioning MTMs between the transmitter (Tx) and receiver (Rx) coils, the efficiency and range of WPT systems can be significantly enhanced. MTMs exhibit unique properties, such as negative refraction and evanescent wave amplification, which are particularly promising for improving PTE in WPT systems. At a separation distance of 70 mm, the implementation of negative permittivity MTMs and double-negative MTMs yields a remarkable improvement in PTE, achieving an increase of 180% compared to a conventional WPT system without MTM integration. Systems with MTM maintain better PTE at increasing lateral and angular misalignments, but at 90° misalignment, power transfer is almost impossible, even with MTM, due to complete misalignment of the fields. This study aims to provide a comprehensive analysis of the development and performance of negative permittivity and double-negative MTM-based WPT systems, offering critical insights into their potential for enhancing WPT efficiency and range.

1. INTRODUCTION

Study in wireless power transfer (WPT) eliminates the need for physical cables, allowing devices to recharge autonomously, thereby reducing user inconvenience. It operates through electromagnetic energy transmission from a transmitter to a receiver, creating a promising foundation for replacing traditional batteries in the future [1]. This system primarily relies on inductive coupling, where electrical energy is transferred through electromagnetic field interactions between two resonating coils [2].

While WPT technology has advanced significantly, it still faces challenges, including efficiency loss as the distance between the transmitter and receiver increases. Near-field WPT systems, particularly those based on resonant inductive coupling, experience sharp declines in PTE due to magnetic field limitations [3]. This issue arises because magnetic field strength decays exponentially with distance, restricting WPT systems to short ranges. Researchers have explored enhancing coil quality factors and optimizing resonant coupling to mitigate these losses, but these approaches remain constrained to near-field applications [4].

To address these limitations, the use of metamaterials (MTMs) has emerged as a promising solution for improving WPT systems. MTMs are artificially engineered structures exhibiting unique electromagnetic properties, such as negative permeability and refractive indices, which are not found in naturally occurring materials [5]. Their ability to amplify evanescent waves enables stronger resonant magnetic coupling between the transmitter and receiver, leading to significant enhancements in both PTE and range [6].

Double-negative metamaterials (DNG-MTMs), characterized by negative permittivity and permeability, have shown considerable improvements in efficiency at specific operating frequencies. Studies report efficiency gains up to 180% when MTMs are strategically positioned between transmitter and receiver coils [7]. Similarly, split-ring resonator-based MTMs enhance power focusing, significantly reducing magnetic flux leakage and extending power transfer distances [8]. MTMs can improve efficiency, range, and issues such as energy loss during far-field transfer, material fabrication complexity, and misalignment sensitivity persist [9]. Researchers are actively exploring optimized MTM designs, such as dual-band metamaterials for multi-frequency operation and wideband stacked structures, to overcome these limitations [10]. Furthermore, hybrid solutions combining MTMs with relay coils or inhomogeneous

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materials are under investigation to improve robustness and efficiency under dynamic conditions [11].

This study aims to develop a WPT system that integrates advanced MTM structures to enhance near-field resonant coupling and improve PTE over extended distances. Addressing current research gaps in MTM-based WPT systems will enable more efficient, long-range wireless charging solutions for applications ranging from consumer electronics to electric vehicles and implantable medical devices [12].

By systematically analyzing MTM design principles, experimental outcomes, and practical challenges, this study contributes to the development of next-generation WPT technologies capable of achieving high efficiency and robust performance across diverse applications.

2. METHODOLOGY

2.1. Designing Planar Coil

To maximize PTE between the Tx and Rx coils, this study developed an antenna design based on established findings and supported by prior research. A compact coil design was prioritized to account for mobility requirements. FR4 was selected as the substrate material due to its low dielectric loss, ensuring minimal energy dissipation, and its high dielectric constant, which promotes efficient energy coupling between the Tx and Rx coils. Copper was chosen for the coil material because it offers excellent electrical conductivity, mechanical strength, and cost-efficiency, making it well suited for wireless power transfer applications.

Previous studies [13] revealed that square substrates provide higher transfer efficiency than circular ones, guiding the geometric choice for this design. Based on these insights, a three-turn spiral coil, 40 mm × 40 mm and width line 1 mm, shown in Figure 1, was implemented as the optimal antenna configuration to improve wireless power transfer efficiency.

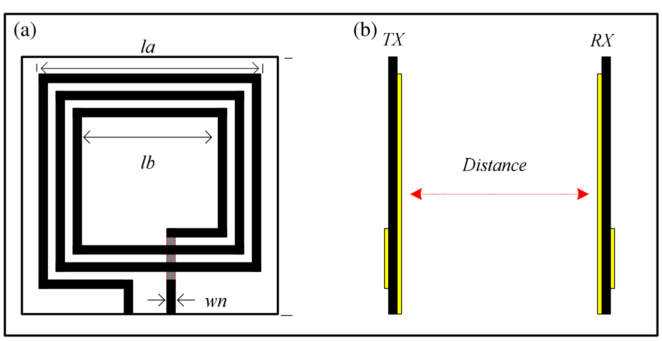

FIGURE 1. (a) Schematic of the antenna coil, and (b) configuration of transmitter (Tx) and receiver (Tx).

The resistance and skin depth δ of each antenna were determined by using,

$$R = \frac{R_{DC}}{4\delta}\left(\frac{t_c}{1-e^{-\frac{t_c}{\delta}}}\right) \quad (1)$$

$$R_{DC} = \rho\sum_{m=1}^{n}\frac{l_m}{A_m}, \quad \delta = \frac{\sqrt{\rho}}{\sqrt{\pi f \mu_o}} \quad (2)$$

Here, ρ represents the resistivity of copper (1.7×10^{-8} Wm), A the cross-sectional area of the loop, l_n the total length of the antenna at n loop, and t_c the thickness of the conductor. The values for A_n and l_n were determined through the following calculations:

$$A_n = w_n \times t_c \quad (3)$$

The calculation was performed to determine the inductance of each antenna by

$$L_{1,2} = \frac{(n^2\mu l_{avg}C_1)}{2}\left[\ln\left(\frac{C^2}{l_p}\right) + C_3 l_p + C_4 l_p^2\right] \quad (4)$$

Here, μ represents the permeability of the background medium, and n is the total number of available turns. The parameters l_{avg} and l_p are defined by:

$$l_p = \frac{l_a - l_b}{l_a + l_b} \quad (5)$$

$$l_{avg} = \frac{l_a + l_b}{2} \quad (6)$$

The coefficients for the Current Sheet Expression, namely C_1, C_2, C_3, and C_4, are 1.27, 2.07, 0.18, and 0.13, respectively. The inductance of the antenna was calculated employing the Modified Wheeler Formula.

$$L_{mw} = \frac{K_1\mu_o\left(n^2 l_{avg}\right)}{1 + K_2 l_p} \quad (7)$$

K_1 and K_2, which are 2.34 and 2.75, respectively, serve as the coefficients for the Modified Wheeler Expression for the square shape coil antenna. The PTE, denoted as η, can be theoretically calculated using parameters such as the coupling coefficient between the transmitter and receiver coils and the quality factor of the resonators. Both formulas offer an approximate approach for determining inductance values. The transfer efficiency of a pair of antennas in an energy transfer link was computed using:

$$\eta = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \quad (8)$$

The calculation involves determining the transfer efficiency of a pair of antennas in an energy transfer link, utilizing the Q-factors of the transmitting and receiving antennas, denoted as Q_1 and Q_2, respectively.

$$Q_{1,2} = \frac{\omega L_{1,2}}{R_{1,2}} \quad (9)$$

$$\omega = 2\pi f \quad (10)$$

The coupling coefficient, denoted as k, represents the interaction between the two antennas and was established through the following calculations:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (11)$$

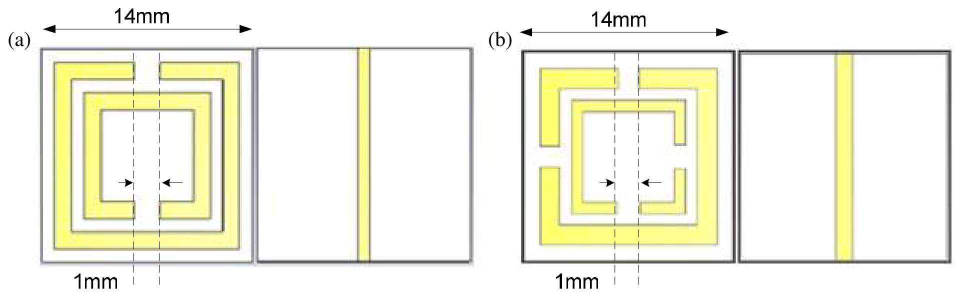

FIGURE 2. Schematic of the (a) MTM-SRR, and (b) MTM-modified SRR.

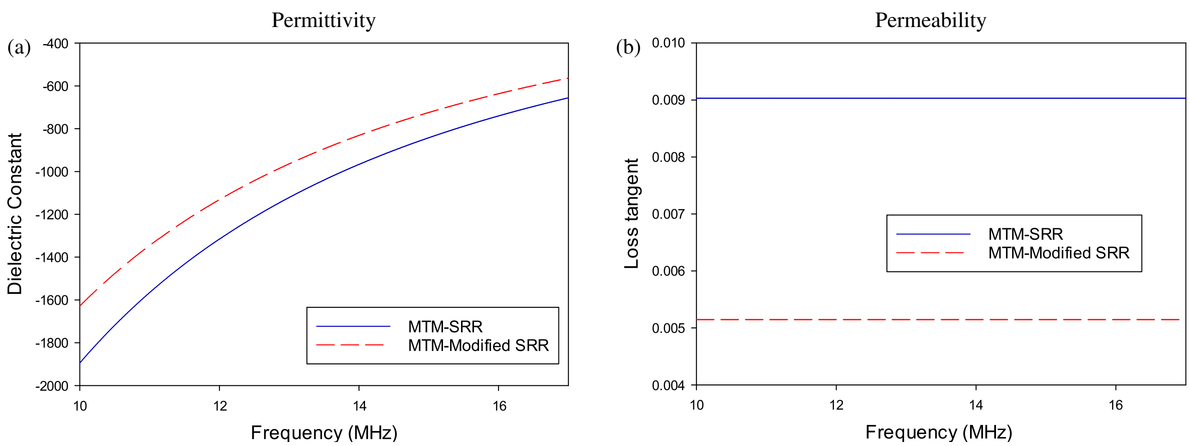

FIGURE 3. Comparison of (a) permittivity and (b) permeability.

2.2. Designing MTMs

In this study, Split Ring Resonator (SRR) design was utilized to fabricate the MTMs. SRRs are a well-known class of MTMs with broad applications in both academic research and practical implementations. SRRs have been typically used to make negative and double negative MTMs. The deviation from traditional norms can be attributed to the distinctive attribute of SRRs, which allows them to exhibit negative electromagnetic properties, distinguishing them from conventional MTM designs that often possess positive features. By undertaking this study, the research not only enhances the practicality of SRRs but also contributes to the broadening of MTM applications, providing a novel viewpoint on the potential utilization of these structures for the development of MTMs with favourable electromagnetic characteristics. MTMs were designed on an FR4 substrate for its low dielectric loss and high dielectric constant, ensuring efficient energy coupling between the transmitter and receiver components.

CST Studio Suite is used to design and simulate the MTM. Two different MTMs were designed, $14\,\text{mm} \times 14\,\text{mm}$, as illustrated in Figure 2. The characteristics for each MTM are observed and analyzed before it is implemented into the WPT system.

The graph in Figure 3(a) compares the dielectric constants of two MTM designs, the standard MTM-SRR and MTM-modified SRR, across a frequency range of 10 to 16 MHz. Both designs display negative permittivity, a key feature of metamaterials, but the MTM-modified SRR maintains a more stable and less negative dielectric constant throughout the frequency range. This stability suggests that the MTM-modified SRR is better at reducing material losses and promoting efficient signal propagation. The enhancements made to the standard SRR design appear to improve its overall effectiveness, making it a stronger candidate for applications requiring precise control of electromagnetic waves.

Figure 3(b) illustrates a comparison of the loss tangent for the same two designs over the same frequency range. The loss tangent measures energy dissipated as heat in the material, with lower values indicating better efficiency. The MTM-modified SRR consistently outperforms the standard MTM-SRR by ex-

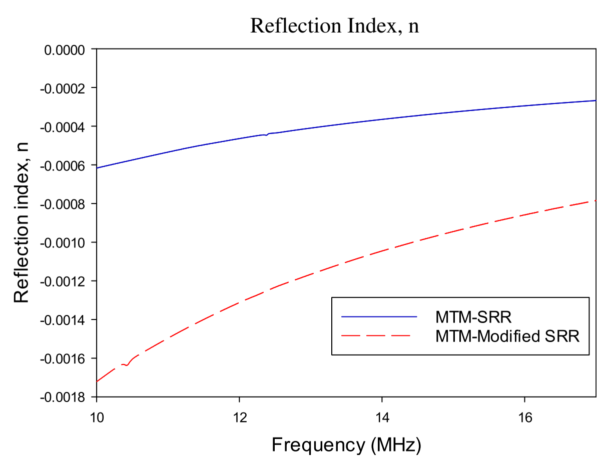

FIGURE 4. Comparison of reflection coefficient.

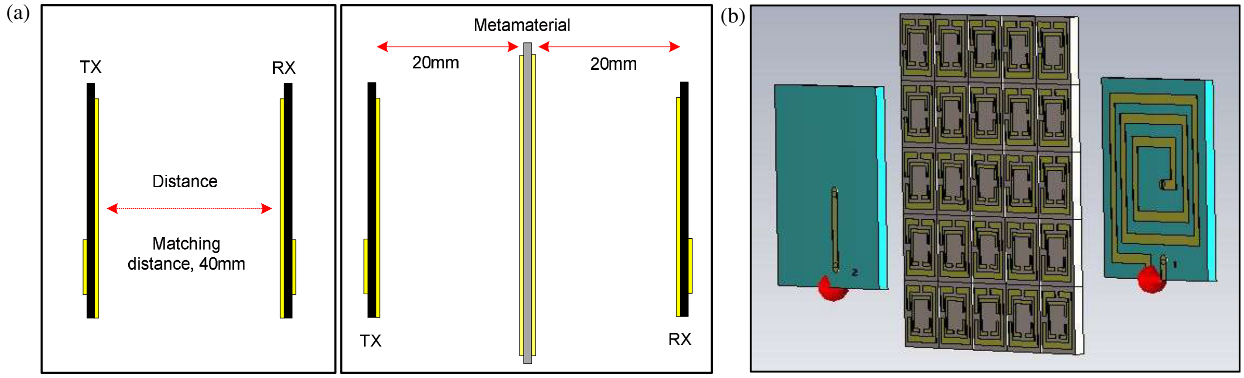

FIGURE 5. Arrangement of Tx and Rx for WPT system (a) 2D and (b) 3D view.

hibiting lower loss tangents, signifying less energy dissipation. Furthermore, the MTM-modified SRR demonstrates superior permeability characteristics and consistent negative permeability compared to the positive permeability seen in the MTM-SRR. The advantage of DNG-MTM over other types of metamaterials lies in its ability to enhance electromagnetic properties such as transfer efficiency and miniaturization [14]. This indicates that the MTM-modified SRR is more effective at minimizing electromagnetic wave losses, efficiently reflecting and focusing the waves.

In Figure 4, the reflection indices of the two designs are compared across the frequency range. While both designs show a negative reflection index, the MTM-modified SRR consistently exhibits a less negative value, indicating superior transmission properties. This means that the MTM-modified SRR allows more energy to pass through with less reflection, resulting in improved electromagnetic performance. The design adjustments to the standard SRR structure have clearly optimized its properties, making the MTM-modified SRR a more effective solution for applications requiring efficient energy transmission and minimal reflection.

Both designs resulted a negative refractive index. However, the MTM-modified SRR design stands out with its double-negative characteristics, which significantly enhance its ability to manipulate electromagnetic waves. This feature improves wave focusing, boosts resonant energy transfer, and increases the overall efficiency of WPT. Additionally, it minimizes electromagnetic losses, resulting in stronger and more stable near-field coupling. This advantage is particularly beneficial for long-range and efficient WPT systems, where precise wave control is essential for optimal performance. The frequency matching ensures efficient energy transfer without considering the properties of MTM at different frequencies.

2.3. WPT System Performance

The performance of the WPT system is evaluated by implementing an MTM structure strategically placed at the midpoint between the Tx and Rx coils, as illustrated in Figure 5(a) and Figure 5(b). This study investigates the impact of the MTM on PTE by systematically varying the distance between the Tx and Rx. This approach enables a thorough analysis of the MTM's role in enhancing wireless power transfer across different separation distances, providing valuable insights into its ability to influence electromagnetic wave propagation and improve system efficiency.

To ensure optimal system performance, a lumped element matching technique is employed to tune the resonance frequency to 13.56 MHz. This frequency is a widely accepted standard for WPT systems, particularly in near-field applications, where precise resonance is critical for achieving impedance alignment between the transmitter and receiver. The matching process, as illustrated in Figure 6, minimizes energy losses and ensures efficient power transfer, using lumped element approach.

The MTM structure, known for its unique electromagnetic properties, especially negative permittivity and permeability, is able to manipulate electromagnetic waves and improve the efficiency of power transfer. These characteristics enable the MTM to enhance resonant coupling and reduce energy dissipation, particularly in scenarios where the separation distance between the Tx and Rx coils increases.

Experimental results obtained at different distances will provide critical data on the MTM's effectiveness in improving wireless power transmission. This combination of advanced materials and precise resonance tuning represents a promising direction for achieving highly efficient and adaptable WPT systems capable of operating effectively over variable distances.

3. RESULT AND DISCUSSION

In order to investigate the enhancement of PTE, a WPT system was configured with three distinct arrangements: without metamaterials, with a standard Split Ring Resonator (MTM-SRR), and with a Modified Split Ring Resonator (MTM-modified SRR). Each setup was designed to evaluate and compare the impact of the MTM structures on PTE, focusing on their ability to influence electromagnetic wave propagation and improve system performance. The PTE was simulated and recorded for varying distances between the Tx and Rx coils in all three configurations. To ensure fair comparison and optimal system performance, a lumped element matching network technique was employed to match the resonance frequency of the antenna coils

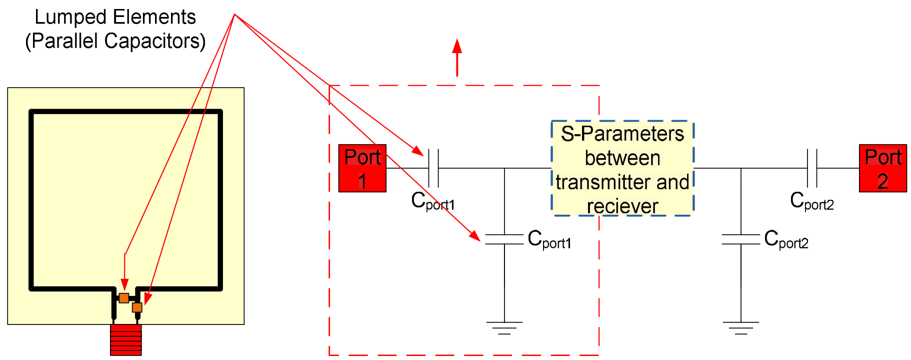

FIGURE 6. The Mini Match macro in CST for matching purpose using lumped element approach.

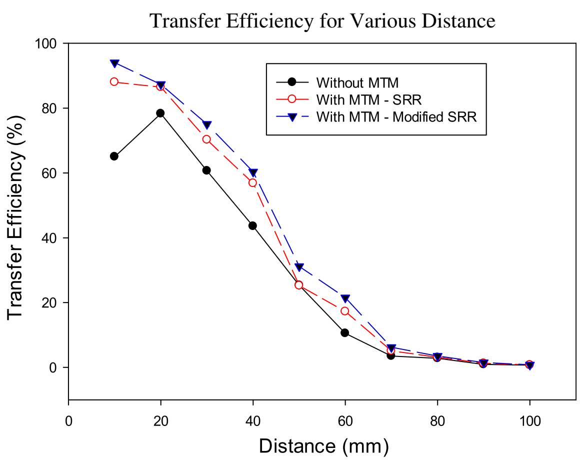

FIGURE 7. Graph transfer efficiency at different distance.

to 13.56 MHz in each case to ensure maximum energy transfer and minimizing losses.

Figure 7 shows the significant differences in PTE among the three WPT system configurations. The presence of MTMs significantly enhances the system's wireless transfer efficiency, as depicted by the blue line in the graph, which consistently outperforms the red and black lines representing setups without MTMs or with standard SRR MTMs. This underscores the critical role of MTMs in improving flux density and overall system performance.

The modified SRR MTM configuration demonstrates the highest PTE across the entire range of tested distances. At shorter distances, such as 20 mm, the modified SRR setup achieves an exceptional efficiency of over 90%, reflecting optimal power transmission. In contrast, the absence of MTMs leads to significant interference caused by multi-resonance effects within the system. These destructive interference patterns, resulting from misalignment in electromagnetic coupling between the Tx and Rx coils, cause a sharp reduction in efficiency. As the distance increases, the efficiency of all setups declines; however, the modified SRR MTM configuration remains superior, maintaining approximately 60% efficiency at 40 mm, compared to the reduced performance of the other setups.

The modified SRR MTM's double-negative properties play an important role in enhancing electromagnetic coupling and achieving higher PTE. In comparison, single-negative MTMs offer less significant improvements, further solidifying the modified SRR MTM as the most effective design for enhancing WPT systems. The configuration without MTMs consistently exhibits the lowest efficiency, which decreases sharply with increasing distance. This is attributed to the lack of a resonant structure to enhance coupling between the Tx and Rx coils, resulting in substantial energy losses.

To evaluate the efficiency of the planar loop antenna and MTM design, a separation distance of 40 mm was selected for fabrication and testing. This distance approximates the typical operating range for compact mobile devices, where space constraints are critical. The fabricated antenna and MTM components were measured and tested to reflect real-world wireless charging scenarios for small devices, emphasizing the importance of maintaining a compact and efficient form factor as shown in Figure 8.

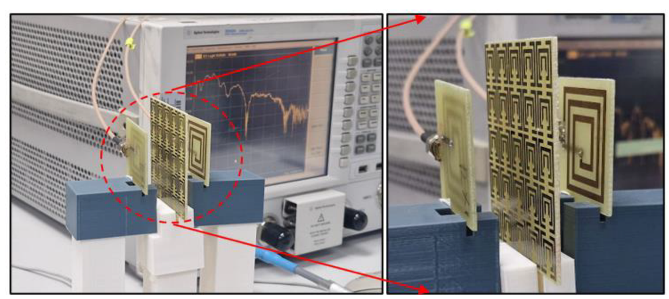

FIGURE 8. Measurement in-lab setup for WPT system.

The experimental measurements and simulation results reveal a consistent pattern, as shown in Figure 9. The simulation model effectively predicts the system's behaviour, with a close correlation observed between the resonance patterns and PTE. This strong agreement highlights the accuracy of the theoretical model and confirms that the fabricated planar loop antenna and MTM closely match the anticipated electromagnetic properties. Among the three configurations, the WPT system implementing the modified SRR MTM demonstrates the highest PTE, outperforming both the standard SRR MTM and the setup without MTMs. These results validate the effectiveness of double-negative MTMs in enhancing the performance of WPT systems. By manipulating the flux direction and improving electromag-

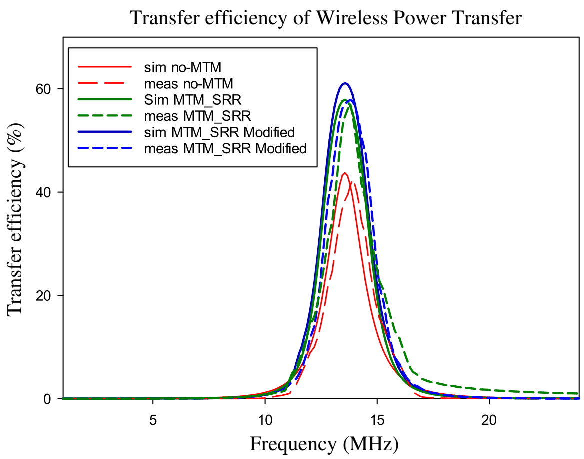

FIGURE 9. Comparison of PTE between different WPT system arrangements.

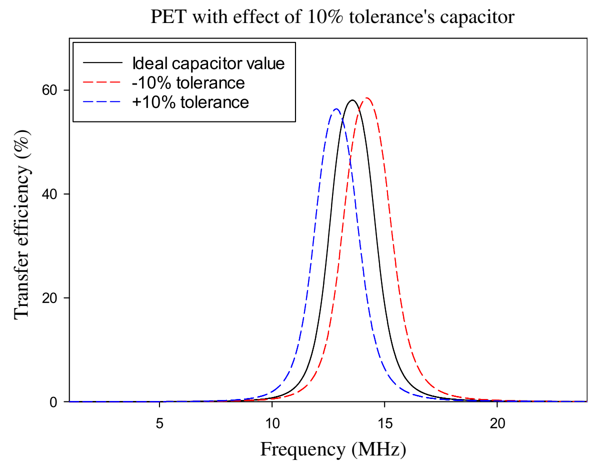

FIGURE 10. PTE with the effect of 10% tolerance's capacitor.

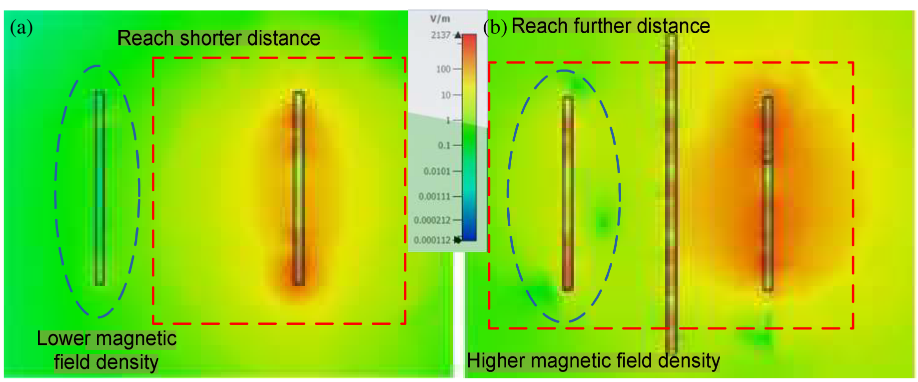

FIGURE 11. Surface current distributions for (a) no MTM and (b) MTM implementation.

netic coupling, the modified SRR MTM significantly boosts the PTE, confirming its superior capability for optimizing wireless power transfer systems.

Despite the strong alignment between the simulated and experimental results, minor discrepancies were observed, primarily due to imperfections in the lumped elements used in the matching circuit. These components, with a tolerance level of 10%, introduced variations in inductance and capacitance values, leading to slight shifts in the actual resonance point as shown in Figure 10. Such variations affect the precision of the system's resonant frequency and contribute to the differences between simulated and measured results. Nonetheless, the overall agreement between the simulation and measurement trends validates the design approach while emphasizing the influence of component tolerances on system performance.

The superior performance of the MTM-SRR and MTM-modified SRR can be theoretically attributed to their ability to manipulate the electromagnetic field. This capability enhances the coupling between the transmitter and receiver coils, particularly over greater distances. The MTM-modified SRR offers an optimized design that aligns the electromagnetic field more effectively between the coils. This results in reduced reactive power losses and a sustained high level of efficiency across a broader range of distances, making it a highly effective solution for improving wireless power transfer systems.

Figure 11 highlights the significant differences between the configurations of the WPT system with and without the integration of MTMs. The implementation of MTMs results in a significantly higher concentration of magnetic flux, as indicated by the intensified red coloration in the figure, compared to the noticeably weaker pattern observed when MTMs are not present. This contrast highlights the critical role of MTMs in enhancing flux density within the WPT system.

Furthermore, the observed results provide insistent evidence of the MTM's ability to modify and redirect electric current paths, thereby increasing the induced current at the Rx end. The implementation of double-negative MTM topologies has been shown to optimize the inward refraction of flux towards the Rx region, creating an environment highly promising for efficient energy transfer. The ability of MTMs to manipulate flux trajectories represents a significant advancement in wireless energy transfer technology, paving the way for transformative improvements in system efficiency and performance. This breakthrough highlights the potential of MTMs to redefine the boundaries of WPT capabilities.

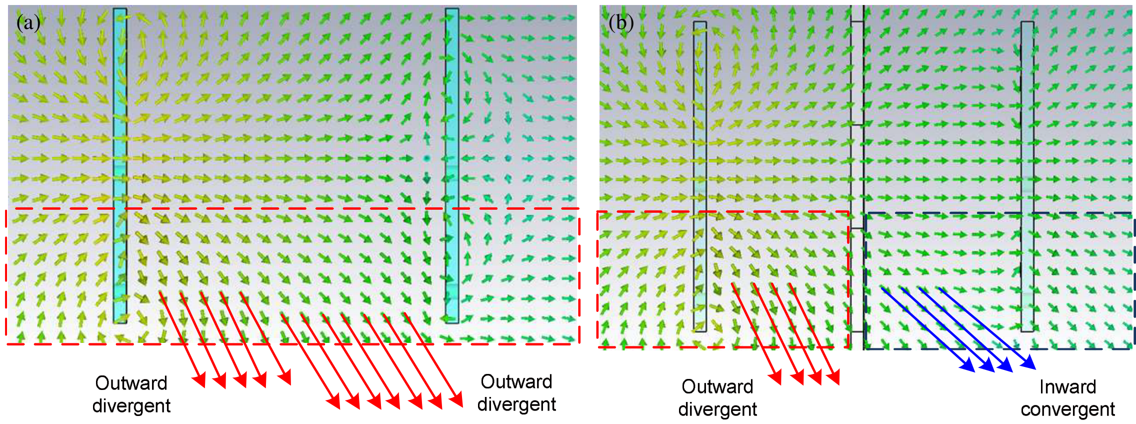

FIGURE 12. Flux direction for WPT system with (a) no MTM and (b) MTM implementation.

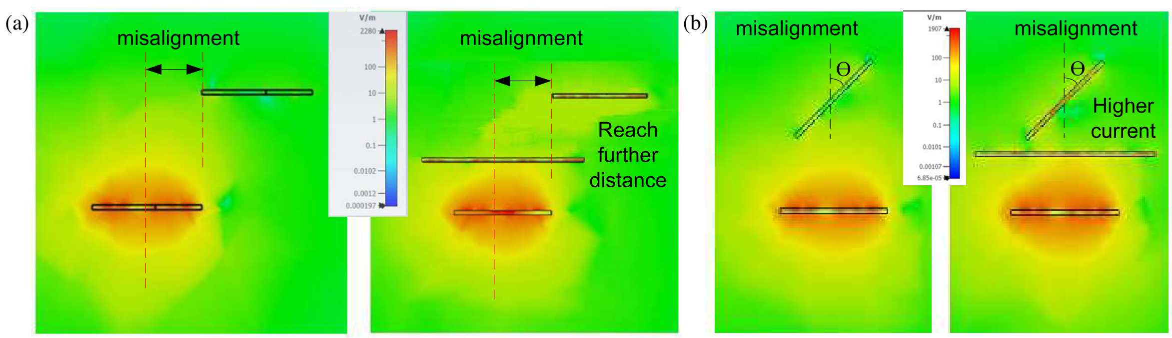

FIGURE 13. (a) Lateral misalignment and (b) angular misalignment.

Figure 12 provides valuable insights into the behaviour of electromagnetic waves within the WPT system by illustrating the flux direction. In the non-appearance of MTMs, as shown in Figure 12(a), the flux exhibits an outward divergence pattern. This outward dispersion reduces the number of flux lines interacting with the primary side antenna coil, leading to a diminished induced current. Using the right-hand rule to analyze the flux direction reveals a circular motion that causes the flux to move away from the receiver area. This outward divergence limits energy transfer efficiency, as a substantial portion of the magnetic flux fails to intersect with the PSC.

Conversely, Figure 12(b) demonstrates the effect of incorporating MTMs, which redirects the flux inward toward the receiver area. This adjustment in flux direction, made possible by the unique properties of the MTM structure, enhances the interaction between the magnetic flux and the receiver, thereby improving energy transfer efficiency. Despite the MTM layer being only 1.6 mm thick, its ability to manipulate the flux trajectory significantly impacts the system's performance, as evidenced by the marked enhancement in transfer efficiency.

In WPT systems, both linear and angular misalignments between the transmitter and receiver significantly affect PTE, as shown in Figure 13. As the receiver moves away from its optimal position, the magnetic flux captured by the receiver coil decreases, causing a noticeable drop in efficiency, particularly in systems without MTM. Referring to Figure 14, at 0 mm lateral misalignment, both systems (with and without MTM) achieve optimal power transfer. However, as misalignment increases, the PTE begins to decrease. In systems without MTM, the weakening flux interaction leads to a more significant drop in efficiency, whereas MTM helps to focus the electromagnetic fields, reducing the decline in efficiency.

Figure 15 shows that at 20 mm of misalignment, the loss in efficiency becomes more pronounced in systems without MTM, as the coupling weakens significantly. The E-field and H-field misalign with the receiver, reducing the energy transfer. In contrast, MTM maintains a reasonable level of power transfer by focusing the fields, ensuring better flux capture. At 40 mm, the difference becomes even clearer: without MTM, power transfer is nearly impossible, with PTE dropping to just 12%. However, with MTM, the system still transfers about 35% of the power due to the enhanced focusing of the fields.

In terms of angular misalignment, the efficiency of power transfer is highly dependent on the alignment of the coils. At 0° misalignment, both coils are perfectly aligned, ensuring maximum PTE. In MTM systems, PTE remains stable even at angular misalignments of 15° and 30°, demonstrating the ability of MTM to maintain effective coupling despite angular deviations and become the significant finding in this research. However, as the misalignment increases to 45°, the PTE begins to decline. Systems without MTM show a significant reduction in efficiency with even slight angular misalignment. At 60°,

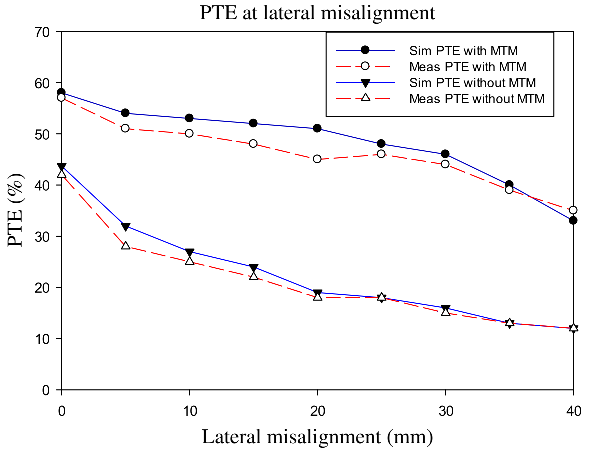

FIGURE 14. PTE at lateral misalignment.

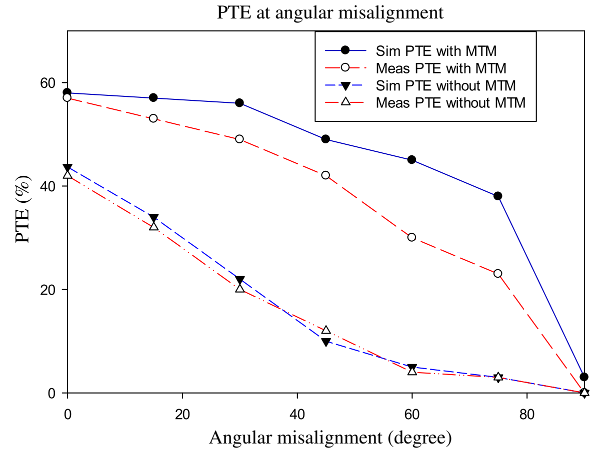

FIGURE 15. PTE at angular misalignment.

the MTM system only experiences a 20% drop in PTE, while a system without MTM shows a drastic decrease to just 3%, emphasizing the robust performance of MTM in mitigating misalignment effects. At 90°, when the receiver is perpendicular to the transmitter, nearly no power is transferred, even with the MTM enhancement, due to the complete misalignment of the electromagnetic fields.

This subtle yet crucial redirection mechanism within the MTM structure highlights the transformative role of MTM technology in WPT systems. By strategically manipulating flux patterns, MTMs enable more efficient and reliable energy transfer, advancing the development of high-performance wireless power transfer solutions.

Notably, the implementation of double-negative MTMs further amplifies these benefits. Unlike MTMs with only negative permittivity, double-negative MTMs enhance both magnetic and electric field interactions, resulting in superior electromagnetic coupling between the transmitter and receiver coils. This leads to significantly higher PTE and more stable performance, particularly over longer distances where single-negative MTMs struggle to sustain efficient energy transfer due to weaker field manipulation. As a result, double-negative MTMs present a robust and effective solution for optimizing WPT systems, offering substantial improvements in efficiency and system stability.

4. CONCLUSION

In conclusion, this research demonstrates that the implementation of various MTM designs can significantly enhance the efficiency of resonant energy transmission in WPT systems. Simulations reveal that integrating MTM-SRR and MTM-modified SRR structures between the transmitting and receiving antennas notably improves the coupling coefficient between the resonators compared to systems without MTMs. These findings highlight the potential of MTMs in optimizing WPT systems and feature the need for further exploration of suitable MTM configurations. While the proposed design focuses on magnetic resonant coupling, the principles outlined in this study can be broadly applied to systems utilizing evanescent wave coupling and may even extend to electrically coupled systems. The study demonstrates significant improvements in PTE for near-field WPT systems, while acknowledging the importance of assessing the design's applicability in real-world and larger-scale applications. The integration of DNG-MTMs shows promise for scalability, as their unique electromagnetic properties can be adapted for longer distances and higher power levels. However, practical challenges, such as material costs, fabrication complexities, and the uniformity of MTM performance over large areas, must be addressed to ensure the system's feasibility in real-world environments. Future work will explore these aspects by testing the MTM-based WPT system in larger-scale scenarios, such as for electric vehicles and industrial applications. Additionally, the optimization of MTM designs will be investigated to accommodate larger power transfer ranges while maintaining efficiency. A more detailed discussion on the scalability of the design will be included, focusing on potential solutions and further research needed to enhance the practicality and robustness of the proposed WPT system for broader applications. Among the configurations tested, the MTM-modified SRR, characterized by its double-negative properties, delivers the highest performance enhancements. Its ability to sustain high transfer efficiency across varying distances makes it particularly valuable for WPT applications where maintaining consistent performance over a range of operating conditions is critical. As the misalignment between the transmitter and receiver increases, systems with MTM maintain better PTE than those without, even at significant lateral and angular misalignments. However, at 90° misalignment, where the receiver is perpendicular to the transmitter, power transfer becomes almost impossible, even with MTM, due to complete misalignment of the fields. The novelty of this work lies in the reduction of power loss and the enhancement of PTE stability in both lateral and angular misalignments, achieved through the use of MTM. Additionally, the compact size of the MTM contributes to a more efficient and space-saving system, making it well suited for practical applications. The results emphasize the transformative role of advanced MTM designs in optimizing WPT systems, facilitating more efficient and versatile energy transmission technologies. Continued research into MTM development is essential to unlocking their full potential in wireless power transfer applications.

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