FOREX Publication
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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 13, Issue 1 | Pages 30-36 | e-ISSN: 2347-470X

Transfer Efficiency Enhancement using Double Negative Metamaterial in Wireless Power Transfer System

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ABSTRACT- Recently, there have been a lot of inventions and development in the field of wireless power transfer (WPT), which has increased the need for WPT systems with high power transfer efficiency (PTE) and longer transmission distances for end users. However, several of the presently accessible WPT systems exhibit restricted PTE and transmission range as a result of their utilization of inductive coupling. In addition, the PTE experiences a significant decline as the separation between the transmitter and receiver coils grows while employing this methodology. Hence, this study presents a proposal for the design of inductive WPT using metamaterials (MTMs) to improve PTE through the manipulation of magnetic field refraction. The efficiency and range of WPT can be enhanced by implementing MTMs between the transmit (Tx) and receive (Rx) coils. MTMs possess characteristics such as evanescent wave amplification and negative refractive properties, which hold promises for enhancing PTE. At separation of 70 mm, the use of negative permittivity MTM and double negative MTM results in a significant improvement in PTE, with an increase of 230% compared to the WPT system without MTM implementation. The purpose of this study is to offer a comprehensive understanding of the development of negative and double negative MTM-based WPT systems.

Keywords: wireless power transfer; power transfer efficiency; negative permeability; negative permittivity; double negative metamaterial.

ARTICLE INFORMATION

Author(s): Muhammad Sukriyllah Yusri, Mohamad Harris Misran, Maizatul Alice Meor Said, Mohd Azlishah Othman, Azahari Salleh, Ridza Azri Ramlee, Norbayah Yusop, Shadia Suhaimi, and Mohd Zahid Idris;

Received: 11/10/24; **Accepted:** 17/03/25; **Published:** 30/03/25;

E- ISSN: 2347-470X;

Paper Id: IJEER240426;

Citation: 10.37391/ijeer.130105

Webpage-link:

https://ijeer.forexjournal.co.in/archive/volume-13/ijeer-130105.html

crossref member CROSSREF.ORG THE CITATION LINKING BACKBONE

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1. INTRODUCTION

In the current age of electronic devices like smartphones and laptops, wireless power transfer (WPT) has become a crucial technology for enabling cordless charging. This technology allows devices to recharge autonomously, eliminating the need for physical cables. WPT operates by transmitting electrical energy from a transmitter to a receiver via an electromagnetic field, creating the potential to eliminate conventional batteries in the future [1]. For this system to function, devices must be equipped with receivers and positioned within the range of the transmitter. The transfer of energy occurs through electromagnetic coupling between two coils, with resonant objects absorbing energy more efficiently than non-resonant ones [2].

While WPT has gained significant attention for applications such as cell phone charging, vehicle electrification, and advancements in medical equipment, it faces certain limitations. One challenge is the efficiency loss as the distance between the transmitter and receiver increases [3]. This problem arises from the nature of near-field energy transfer, which relies on magnetic field coupling. To address this, researchers focus on enhancing the coil quality factor and optimizing magnetic coupling to extend the power transfer range [4]. However, near-field methods, such as resonant inductive and capacitive coupling, remain restricted by limited distances [5].

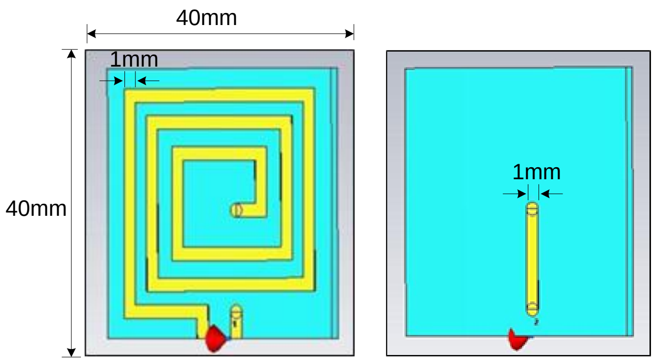
On the other hand, long-distance energy transfer falls under electromagnetic radiation, which is suitable for extended-range applications but suffers from power losses. Techniques like transmitting power *via* microwaves or lasers offer potential solutions but are limited by the challenge of optimizing efficiency due to these inherent losses [6-7].

The most common method for WPT today is inductive coupling, which is based on the principle of electromagnetic induction, by applying an electrical current to a transmitter coil to generate a magnetic field. A secondary receiver coil placed within the range of this field induces an electric current, enabling energy transfer. Inductive coupling has become the foundation for many wireless charging applications, though its range is limited by magnetic field constraints [8-10].
Recent advancements in metamaterials (MTMs) offer a potential solution to these limitations [11]. MTMs are artificially engineered structures with unique properties, including negative refraction. They are designed to enhance the efficiency of wireless power transfer by leveraging their ability to manipulate electromagnetic waves [12]. One of the key features of MTMs is their potential to amplify evanescent waves, which are critical for resonant magnetic coupling. By amplifying these waves, MTMs can enhance the coupling between two resonators, potentially extending the range and efficiency of WPT systems [13-14].

Despite the potential of MTMs, a research gap exists in fully harnessing their capabilities for WPT. While the concept of using MTMs to improve wireless power efficiency has been explored, practical designs that can effectively extend the power transfer distance without significant losses remain underdeveloped [15]. Addressing this gap could lead to more efficient wireless charging systems for a broader range of applications [16].

2. METHODOLOGY

In order to obtain the most efficient PTE between the Tx and Rx coils, the antenna design in this study was influenced by established characteristics shown in Table 1, including findings from prior research. The mobile characteristic is considered in designing the coil small. The low dielectric loss features of FR4 ensure excellent power transmission with minimal energy dissipation. Copper was chosen as the coil material because it provides a good balance of electrical performance, mechanical durability, and cost-effectiveness for wireless power transmission coils. A review of existing literature [10] influenced the decision to utilize a square substrate shape, which indicated greater transfer efficiency compared to circular substrates. Based on this discovery, the study advocated a spiral coil form with three turns, as shown in *figure 1*.



(a) (b)
Figure 1. Schematic of proposed antenna coil

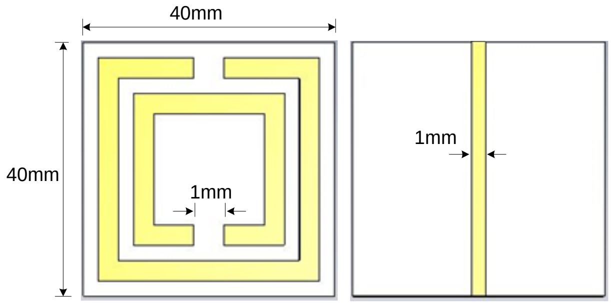
The PTE, η can be calculated theoretically using equations 1 and 2 below.

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

Where Q_1 and Q_2 are the Q-factors of the antennas. k is the coupling coefficient between both antennas, determined using

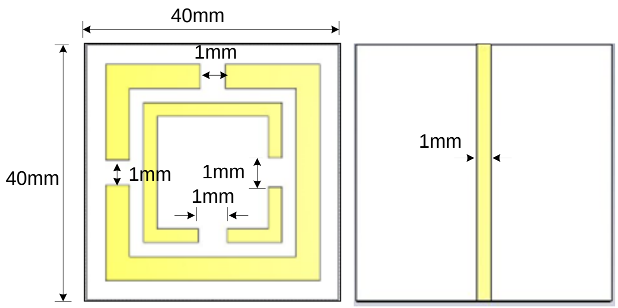
$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (2)$$

For this investigation, the single unit split ring resonator (SRR) design was employed to fabricate MTMs, as illustrated *in figure 2*. SRR are a widely recognized subset of MTMs that have numerous uses in both academic research and practical use. These buildings are characterized by a circular band made of metallic material with a central aperture. When an electromagnetic wave comes into contact with the SRR, it induces a magnetic dipole moment in the ring, causing a decrease in permeability. In this study experiment, FR4 substrate was used to fabricate MTMs, whereas copper was employed for the coil component.



(a) top (b) bottom
Figure 2. SRR MTMs design

Referring to *figure 3*, the SRR structure was optimized to enhance the sensor's performance by modifying its design, which alters the surrounding electromagnetic field. This adjustment improves the sensor’s resonance characteristics and impedance matching. By fine-tuning the SRR configuration, the sensor's sensitivity and overall effectiveness were significantly increased, leading to more accurate and reliable measurements.



(a) top (b) bottom
Figure 3. Modified SRR MTMs design

SRRs have typically been used to make negative and double negative MTMs. The alteration from traditional norms can be attributed to the distinctive attribute of SRRs, which allows

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them to exhibit negative electromagnetic properties and contributes to the broadening of MTM applications, providing a novel viewpoint on the potential utilization of MTM with favorable electromagnetic characteristics.

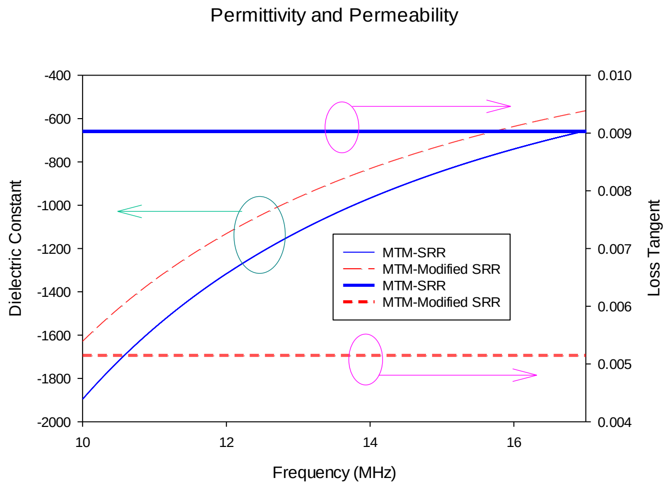

Figure 4. Comparison of permeability

The graph in *figure 4* compares the dielectric constant of MTM-SRR and Modified SRR MTM. Both designs exhibit negative permittivity, but the Modified SRR MTM shows a more stable and less negative dielectric constant. This suggests improved performance with reduced material losses and better signal propagation, making it a superior choice for precise electromagnetic wave control. A lower loss tangent indicates better energy efficiency, and the Modified SRR MTM consistently outperforms MTM-SRR. With its negative permeability and reduced energy loss, it enhances wave reflection and focusing, making it ideal for applications requiring minimal signal attenuation and improved efficiency.

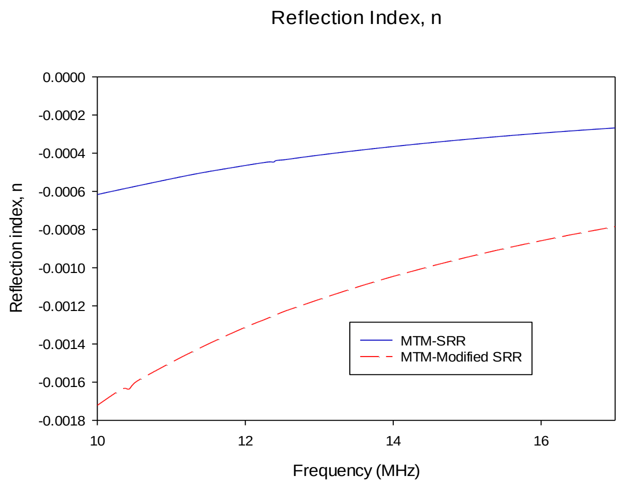

Figure 5. Comparison of reflection coefficient

Figure 5 compares the reflection index of MTM-SRR and Modified SRR MTM over 10 to 16 MHz. A lower reflection index indicates better wave transmission, and the Modified SRR MTM consistently shows less negative values. This suggests improved transmission properties, allowing more energy to pass through. Structural modifications optimize its electromagnetic performance, making it a better choice for enhanced signal propagation.

Although both designs possess a negative refractive index, the Modified SRR MTM design offers a double-negative characteristic, which enhances electromagnetic wave manipulation. This double-negative feature improves wave focusing, increases resonant energy transfer, and enhances the efficiency of wireless power transfer. Additionally, it reduces electromagnetic losses, resulting in stronger and more stable near-field coupling, which is advantageous for long-range and efficient WPT systems where precise wave control is crucial for performance enhancement.

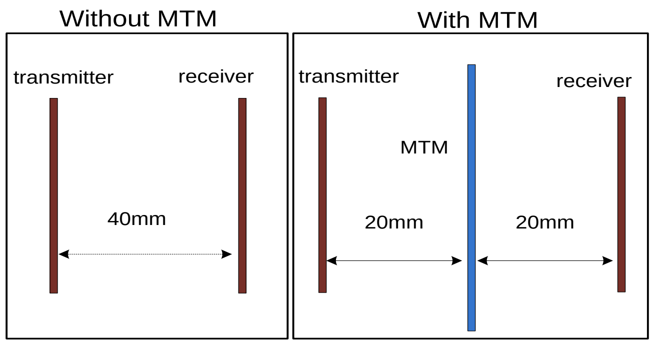

Figure 6. Setup configuration between the antennas

The efficacy of the wireless power transfer system is assessed by incorporating a MTM structure strategically positioned at the midpoint between the Tx and Rx, as shown in *figure 6*. The study examines the impact of the MTM on PTE by altering the distance between the transmitter and receiver. This method enables a comprehensive analysis of the MTM's function in improving wireless power transfer across varying separation distances, offering insights into its ability to affect electromagnetic wave propagation.

A lumped element matching technique is employed to adjust the resonance frequency to 13.56 MHz to reduce energy losses, hence optimizing power transfer over varied distances.

3. RESULTS AND DISCUSSION

In order to assess the efficiency of a coil antenna under varying distances, antenna coil was set up and simulated in a controlled laboratory environment. The MTM performance at various matching distances was investigated by systematically adjusting the distance between the Tx and Rx antennas. The results indicated that the MTM's efficiency in enhancing the antenna system's overall performance could be significantly affected by the precise adjustment of the distance.

Figure 7 demonstrates the significant difference between the configurations of the WPT system that integrate MTM and those that do not. It is important to note that the presence of MTM leads to a significantly higher wireless transfer efficiency, as evidenced by the blue line, in contrast to the red and black line pattern that is relatively less pronounced in the absence of MTM. The important function of MTM in improving the flux density of the WPT system is evident in the significant disparity.

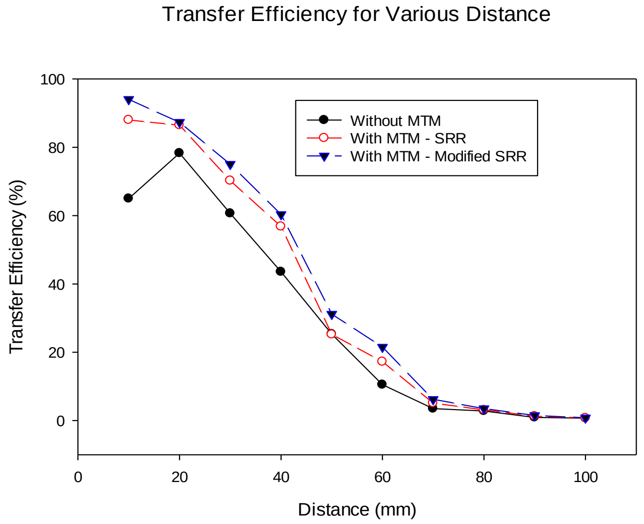

Figure 7. Graph transfer efficiency at different distance

The graph indicates that the setup with the modified SSR MTMs obtains the highest transfer efficiency across the whole range of distances, significantly surpassing the other two setups. In particular, the modified SSR setup achieves an efficiency of over 90% at shorter distances (e.g., 20 mm), indicating optimal power transmission. However, the absence of MTMs results in a significant amount of interference between the system's multiple resonant modes. This is due to the pronounced multi-resonance effects. Destructive interference patterns are the result of the substantial misalignment in the electromagnetic coupling between the Tx and Rx coils caused by these undesirable resonances. Subsequently, the transfer efficiency undergoes a sharp reduction. Efficiency gradually decreases as the distance increases, but it remains superior to the other setups. Double-negative MTM in modified SSR MTM provide superior enhancement in wireless power transfer systems compared to single negative-permittivity MTMs, offering improved electromagnetic coupling and higher transfer efficiency.

The efficiency of the configuration without MTM is consistently the lowest, and it decreases rapidly as the distance increases. This is the result of the absence of any resonant structure to improve the coupling between the Tx and Rx coils, resulting in a significant energy loss.

Figure 8 illustrates the enhancement in transfer efficiency of the PSC system with MTMs across various distances in simulation. The results show that MTMs improve efficiency, but the benefits vary with distance, indicating a complex interaction between MTM properties and energy transfer. The improvement is more significant at lower PTE levels, where small increases yield substantial efficiency gains. However, at closer distances, excessive coupling effects, such as eddy current losses and magnetic field leakage, reduce efficiency.

At greater distances, the enhancement percentage is notable, but the absolute PTE values remain low, making precise comparisons challenging. Despite this, MTMs still demonstrate potential for optimizing power transfer across extended distances. A 40mm distance was chosen for measurement, balancing practicality and effectiveness. At this range, PTE improvements are clear and measurable, ensuring an efficient experimental setup.

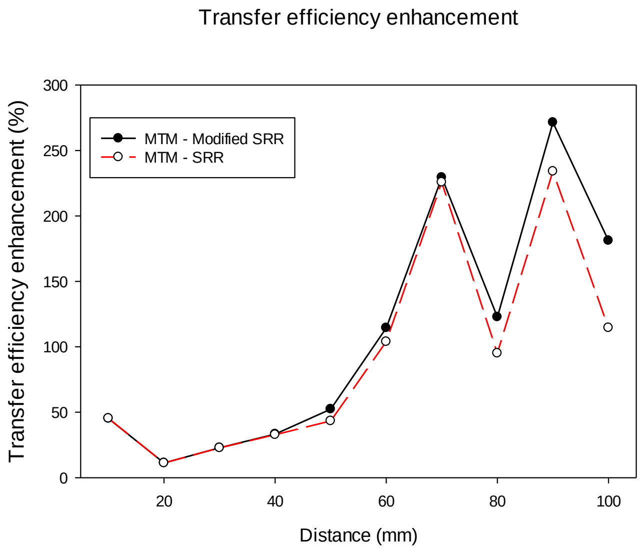

Figure 8. Transfer efficiency enhancement of PSC on simulation at various distance

The efficiency of the planar loop antenna and MTM in a WPT system was validated through fabrication and testing. The fabricated antenna and MTM are shown in *figures 9 (a-c)*.

(a) (b) (c)

Figure 9. Fabricated (a) coil antenna, (b) MTM-SRR, and (c) MTM-Modified SRR

The experimental measurements and the simulation results demonstrate a comparable pattern, as illustrated in *figure 10*. The simulation model accurately anticipates the system's behavior under these conditions, as evidenced by the similar pattern of resonance and PTE. This significant similarity indicates that the fabricated planar loop antenna and MTM exhibit properties that closely align with those predicted by theoretical models. The PTE of the WPT that implement modified SRR MTM has the best PTE compared to the system using SRR MTM and WPT system without MTM. It proves the capability of double negative MTM in manipulating flus direction to enhance PTE of WPT system.

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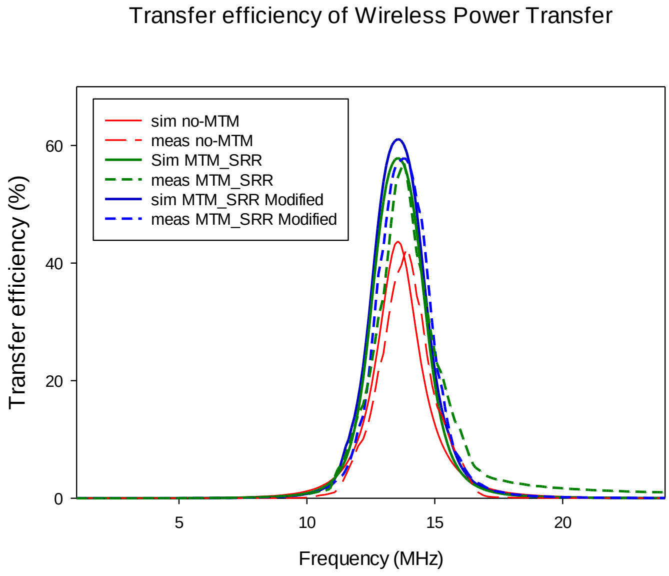
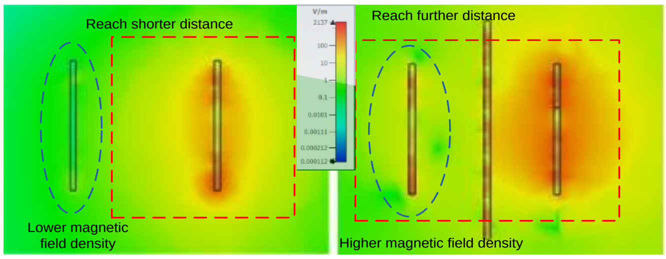


Figure 10. Implementation of MTM between the antennas

Referring to *figure 11*, there are minor disagreements between the simulation and the measurement. Imperfections in the lumped elements employed in the matching circuit are the primary cause of these defects. The precision of the system's resonant frequency could be considerably impacted by the tolerance level of 10% in the components. The actual resonance point is shifted as a result of the variation in inductance and capacitance values, which then contributes to the differences between the simulated and observed results. Nevertheless, the design approach is validated by the general alignment between the simulation and measurement trends, which also highlights the impact of component tolerances on the overall system performance.



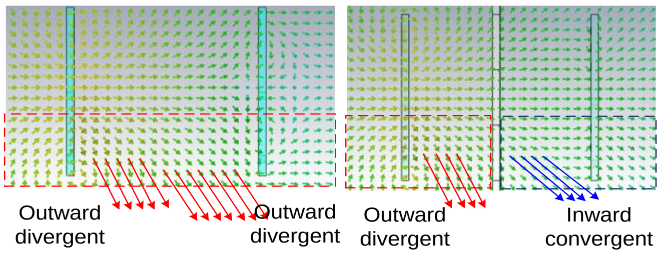
(a) without MTM (b) with MTM

Figure 11. Modified SRR MTMs design

Figure 11 demonstrates the significant difference between the configurations of the WPT system that integrate MTM and those that do not. It is important to note that the presence of MTM leads to a significantly higher concentration in the magnetic field, as evidenced by the intensified red coloration, in contrast to the pattern that is relatively less noticeable in the absence of MTM. The important function of MTM in improving the flux density of the WPT system is evident in the significant disparity.

Additionally, the observed events serve as evidence of the effectiveness of MTM in altering and redirecting the electric current paths to increase the induced current at the RX end. The utilization of double negative MTM topologies has been discovered to improve the inward refraction of flux direction towards the RX region, thereby establishing a more conducive environment for efficient energy transfer.

The empirical evidence presented proves the theory that MTM enhances transfer efficiency by coordinating favorable flow patterns within the WPT system. The manipulation of flux trajectories by MTM represents a substantial advancement in wireless energy transfer technology, indicating a transformative shift towards unparalleled levels of efficiency and performance.



(a) (b)

Figure 12: Modified SRR MTMs design.

Figure 12 illustrates the flux direction, offering significant insights into the behavior of electromagnetic waves within the WPT system. In the absence of MTM, as illustrated in Figure 12(a), the flow has an outward divergence pattern. The dispersion of outward flux leads to a reduced number of flux lines interacting with the receiver, hence causing a diminished induced current. Utilizing the right-hand rule to determine the flux direction shows that the flux exhibits a circular motion, resulting in its departure from the receiver area. The outward flux divergence restricts energy transfer efficiency, as a significant percentage of the magnetic flux does not cross with the receiver.

Nevertheless, the implementation of MTM, as shown in *figure 12(b)*, allows for the manipulation of flux direction to achieve more advantageous results. The analysis of the figure indicates a subtle but important change in the flux direction, which is now orientated inward towards the receiver area. The adjustment of flow direction is enabled by the distinctive characteristics of MTM structures.

Consequently, although the alteration in flux direction could happen within a limited area of the MTM structure, its implications are significant, highlighting the crucial importance of MTM technology in enhancing the efficiency of WPT systems. The implementation of double-negative MTM in a WPT system shows superior enhancement compared to MTMs with only negative permittivity. The double-negative MTM improves both magnetic and electric field interactions, leading to better electromagnetic coupling between the transmitter and receiver coils. This results in significantly higher PTE and more stable performance, particularly at longer distances, where negative-permittivity MTMs alone struggle to maintain efficient energy transfer due to weaker field manipulation. Double-negative MTMs, therefore, offer a more robust solution for optimizing WPT systems. *Table 1* shows the performance comparison between this work against existing works.

Table 1. Performance comparison

Ref	Distance (mm)	Size (mm)	PTE
[18]	40-100	100 x 100	13.23% increase to 23.46% at distance 40mm
[19]	120	110 x 110	PTE increased from 49% to 72%
[20]	160	N/A	64% higher efficiency than inductive WPT at 160
This work	10-100	40 x 40	230% enhancement at 70mm distance

4. CONCLUSION

In conclusion, implementation of various types of MTMs can enhance the efficiency of resonant energy transmission, as demonstrated in this research. Through simulations, the implementation of SRR and modified SRR MTMs design between antennas significantly improves the coupling coefficient of two resonators compared to without MTMs. This suggests that exploring the use of suitable MTMs in WPT should have further investigation. While the proposed design focuses on a magnetic resonant coupled system, the concept presented can apply broadly to systems involving evanescent wave coupling and may extend to electrically coupled systems as well. The modified SSR MTM setup that has double negative characteristics offers the highest enhancement for WPT systems, particularly when maintaining high efficiency over varying distances is critical.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Ministry of Higher Education, Centre for Research and Innovation Management (CRIM) and University Technical Malaysia Melaka (UTeM) for financing this project through FRGS grant numbering FRGS/1/2021/TK0/UTEM/02/52.

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