MJSAT

Malaysian Journal of Science and Advanced Technology

journal homepage: https://mjsat.com.my/



Analysis of Double-Negative Metamaterial Effects on Wireless Power Transfer Performance

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KEYWORDS

Wireless Power Transfer, Double Negative Metamaterial, Power Transfer Efficiency, Negative Permeability, Negative Permittivity

ARTICLE HISTORY

Received 26 July 2026
Accepted 6 October 2026
Available online 20 October 2026

ABSTRACT

Wireless Power Transfer (WPT) is becoming a promising solution to deliver energy without cables for applications including portable gadgets, electric vehicles, and medical devices. However, the efficiency of traditional WPT systems degrades drastically with increasing distance between the transmitter and receiver, owing to weak magnetic coupling and energy losses. This study examines the utilisation of double-negative metamaterials (DNG-MTMs) in a resonant inductive WPT system to improve the power transfer efficiency (PTE) by utilising a modified Square Split Ring Resonator (SSRR) structure. A tiny three-turn spiral coil functioning at 13.56 MHz was designed on a FR4 substrate and used as transmitting and receiving antennas. The modified SSRR metamaterial was modelled and evaluated by utilising CST Studio Suite to obtain the negative electromagnetic properties that can manipulate the magnetic flux and enhance the resonant coupling. The simulation results showed that the suggested metamaterial exhibits negative permittivity in the working frequency range, demonstrating its feasibility for improving WPT. To optimise the magnetic field distribution and the coupling performance, the metamaterial structure was strategically located in between the transmitter and receiver coils. Comparative analyses showed that the implementation of the redesigned SSRR enhanced the transfer efficiency significantly over transmission lengths from 10 mm to 100 mm. The simulated transfer efficiency at the 40 mm spacing was 58.1% and the experimental efficiency was 57.01%, while the system without the metamaterials had 43.7% and 42.5%, respectively. Moreover, the proposed design successfully reduced the effects of overcoupling and undercoupling, while keeping the performance steady under various operating situations. The results indicate that the improved SSRR DNG-MTM may greatly boost the performance of WPT by increasing the concentration of magnetic flux and coupling strength, which is promising for future high efficiency wireless energy transfer applications.

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1. INTRODUCTION

Wireless Power Transfer (WPT) has become a critical technology to enable cordless charging in the present age of electronic gadgets like smart phones, laptops and electric vehicles. This technology allows electronics to charge themselves, without the need of physical cables. Wireless Power Transfer (WPT) is the transmission of electrical energy from a transmitter to a receiver by means of an electromagnetic field and consequently provides the potential to eliminate the conventional batteries in the future [1]. For this system to work devices need to have receivers and be within range of the transmitter. Energy transmission takes place by electromagnetic coupling between two coils, and resonant items absorb energy more efficiently than non- resonant objects [2].

Even though WPT has received much attention for applications such mobile device charging, vehicle electrification, and advances in medical technology but it has several limitations. A problem is the efficiency decrease with the distance increase between transmitter and receiver [3]. This is due to the features of near-field energy transmission which relies on coupling of the magnetic fields. Researchers are focusing on enhancing the coil quality factor and refining the magnetic coupling to extend the power transmission range [4].

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https://doi.org/10.56532/mjsat.v6iS2.820
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However, nearfield approaches such as resonant inductive and capacitive coupling are limited to short ranges [5].

On the other hand, the long distance energy transfer is categorised as electromagnetic radiation, suitable for common applications, but accompanied by power losses. Promising answers are provided by methods like power transfer using microwaves or lasers, but they are limited by the difficulties of improving efficiency due to inherent losses [6-7].

Currently, the most common method of WPT is inductive coupling, which relies on the principle of electromagnetic induction by applying an electric current to a transmitter coil to generate a magnetic field. If in the range of the field there is a second receiver coil, then an electric current is generated. So it is possible to transfer energy. Several wireless charging solutions are based on inductive coupling [8-10] however the range of the inductive coupling is limited by the magnetic field limits. These limitations are addressed by recent progress in metamaterials (MTMs) [11]. MTMs are custom made structures, that are designed for presenting unique features like negative refraction. They are developed to enhance the efficiency of wireless power transfer, by using their ability to manipulate electromagnetic waves [12]. The main feature of MTMs is the capacity to amplify the evanescent waves which are critical for resonant magnetic coupling. MTMs can enhance the coupling between two resonators by amplifying these waves and so perhaps increase the efficiency and the range of WPT systems [13-14].

MTMs have potential but a research need exists to properly exploit their possibilities for WPT. The use of MTMs to improve the efficiency of WPT has been explored, however designs that can substantially increase the power transmission distance with minimal losses are still under development [15]. Overcoming this limitation might lead to more efficient wireless charging systems, useful in a wider range of purposes [16]

2. METHODOLOGY

2.1 Designing Transmitter and Receiver

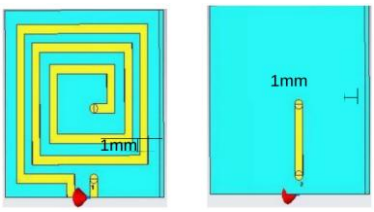
In this work, an antenna design is developed to improve power transfer efficiency (PTE) between the transmitter (Tx) and receiver (Rx) coils. The configuration of a tiny coil was stressed to fulfil the mobility parameters. The substrate material was selected as FR4 because of its low dielectric loss to reduce energy dissipation and high dielectric constant for efficient energy coupling between the Tx and Rx coils. The coil material has been selected as copper, because of its high electrical conductivity, mechanical strength and cost effectiveness, which makes it feasible for wireless power transfer applications. 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

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

Previous research has shown that square substrates are more efficient for transfer than circular substrates [13] and this has guided the choice of geometry in our design.



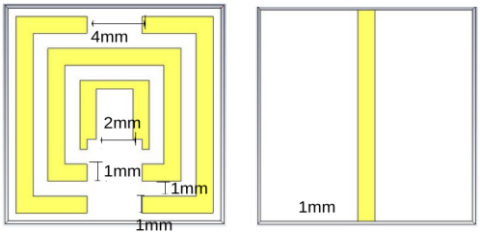
a) Front b) Back

Fig. 1. Antenna for Tx and Rx

Based on these findings, a three-turn spiral coil of 40 mm with a line width of 1 mm in the front and line width of 1 mm with length was implemented as the optimal antenna configuration to improve the efficiency of wireless power transmission as shown in Figure 1.

2.2 Modified Square Split Ring Resonator

Square Split Ring Resonator (SSRR) design was used in this research to fabricate the Metamaterials (MTMs). SSRRs belong to one of the most studied types of MTMs and find common uses both in scientific research and commercial devices. Traditionally, Double Negative Metamaterial (DNG-MTM) have been built with SSRRs. The variation from standard norms may be explained by the specific character of the SSRRs which are designed of exhibiting negative electromagnetic properties, thus differentiating them from common MTM configurations that usually have positive features. The study improves the practicality of SSRRs and broadens the use of MTMs, giving a new viewpoint on the prospective application of these structures to realise MTMs with excellent electromagnetic characteristics. The FR4 substrate was used for fabricating the MTMs because of its low dielectric loss and high dielectric constant, which could allow effective coupling of energy between the transmitter and the receiver. The MTM is designed and simulated using the CST Studio Suite. Figure 2. MTMs of 14 mm by 14 mm have been fabricated. Before implementation in the WPT system, MTM characteristics have been examined and analysed.



a) Front b) Back

Fig. 2. MTM of Modified SSRR

Figure 3 illustrates the dielectric constants of Modified SSRR within a frequency range of 10 to 16 MHz. The designs exhibit a negative dielectric constant over the whole frequency spectrum, indicative of negative permittivity, a fundamental characteristic of metamaterials. This result indicates that the Modified SSRR possesses the capability to minimise material losses and enhance signal propagation, rendering it appropriate for applications necessitating precise control of electromagnetic waves.

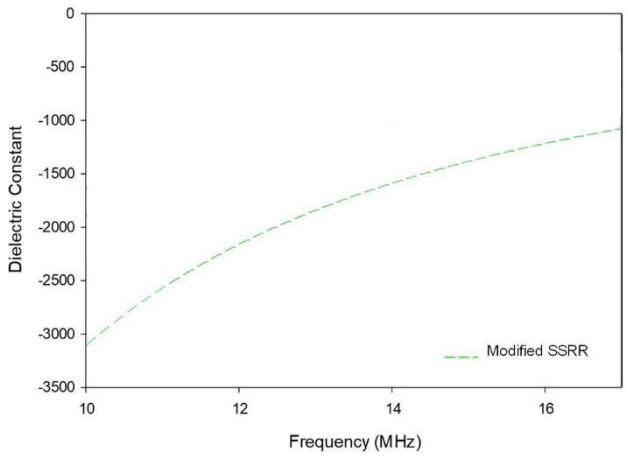


Fig. 3. Dielectric of Modified SSRR

Figure 4 depicts the loss tangent for the identical designs across the equivalent frequency range. Permeability, especially for MTMs, is crucial as it relates to the material's ability to enable the creation of magnetic fields. The loss tangent values, indicating the energy dissipation of the material, show a little rise with increasing frequency, implying a frequency-dependent dissipative property. The loss tangent quantifies energy dissipation as heat within the material, where lower values signify enhanced efficiency. The Modified SSRR regularly demonstrates superior performance by displaying reduced loss tangents, indicating diminished energy dissipation.

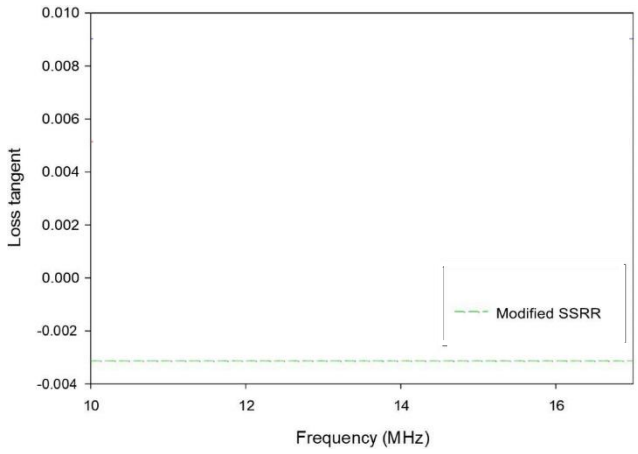
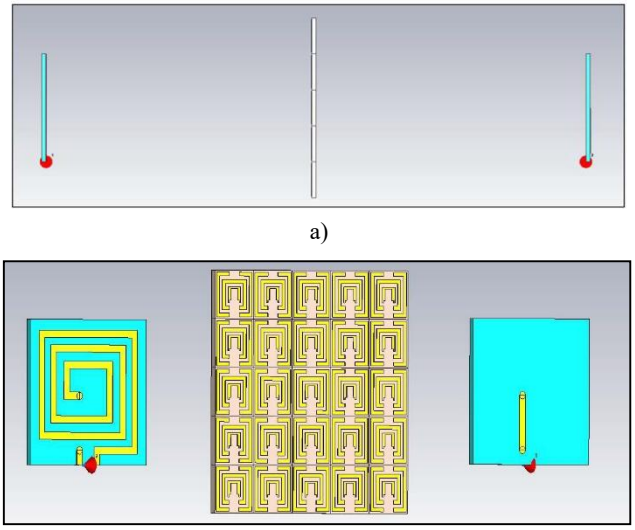


Fig. 4. Loss tangent of Modified SSRR

The Modified SSRR exhibits enhanced permeability properties and maintains consistent negative permeability, indicative of DNG-MTM features. The superiority of DNG-MTM compared to other metamaterial types is attributed to its capacity to improve electromagnetic characteristics, including transfer efficiency and miniaturisation [17]. This signifies that the altered SSRR is superior in reducing electromagnetic wave losses, effectively reflecting and concentrating the waves.

3. RESULT AND DISCUSSION

The MTMs are strategically situated between Tx and Rx, configured to maintain equal spacing on both sides, as seen in Figure 5 a) and b) . The figure shows the precise configuration of the MTMs that form the WPT system. The primary objective of this design is to utilise the unique properties of MTMs to regulate the flow direction, an essential element in optimising energy transmission efficiency. By strategically altering the direction of flow, these MTMs can enhance the overall efficiency of the WPT system, hence facilitating more efficient energy transfer.



a)

b)

Fig. 5. Metamaterial Modified SSRR arrange from (a) 45 degree view and (b) side view

Figure 6 shows the detailed study of the transfer efficiency of the WPT system with different distances from 10mm to 100mm based on the simulation. The graph clearly depicts the influence of MTM implementation on system performance at different distances. The statistics show the ability of MTMs to mitigate efficiency losses due to long operational distance. We may observe the improvement of energy transfer efficiency at different distances by adding MTMs in the system. The transmission efficiency is decreased over long distances because of the lower density of magnetic flux and the loss of the induced current in the WPT system. An under-coupling is a common situation when the interaction between the Tx and Rx is not enough, and hence the energy is not well transferred.

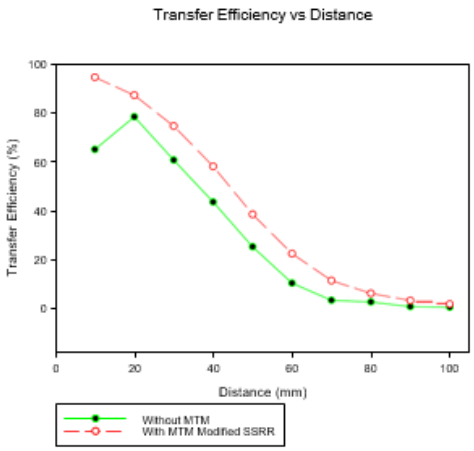


Fig. 6. Transfer Efficiency against Distance of Modified SSRR

However if the coils are too close then an overcoupling effect is produced which increases the inefficiency of the transfer. The overcoupling in the WPT system results in the dual resonance, which leads to the efficiency degeneration. The difference in effectiveness at a distance of 10mm between instances using MTMs and those without them is very clear. The MTM framework needs to be integrated into these

difficulties. Strategic integration of MTM parts into the system permits manipulation of magnetic flux, which offers accurate control of coupling between coils. This will greatly boost transfer efficiency. The harmful consequences of overcoupling can be efficiently managed. The use of MTM technology can better optimize the distribution of flux, make the system work in the specified coupling range, and reduce the occurrence of the dual resonance effect caused by overcoupling. This intricate manipulation of flux marks a paradigm shift in the design of WPT systems, signaling a new age of enhanced efficiency and performance in wireless energy transfer applications.

The findings of this study are very important for the development of WPT systems, especially in cases where operational distances can fluctuate or be unregulated. The integration of MTMs is vital for the significant enhancement of PTE. MTMs are designed with a unique configuration to manage the magnetic flux and guide it towards the receiver region. This leads to more induced current and hence improves the power transfer efficiency.

When it comes to verifying the result from the simulation, it is important to proceed the study to the experimental comparison. An SMA connection was precisely mounted to a FR4 board with soldering methods, among lumped parts, to construct an accurate matching circuit. The antenna was evaluated using a Rohde and Schwarz ZVL Network Analyzer (VNA) at low frequencies within the faculty's laboratory, as seen in Figure 7.

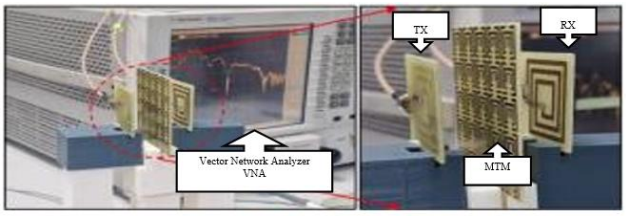


Fig. 7. Experimental setup with Modified SSRR

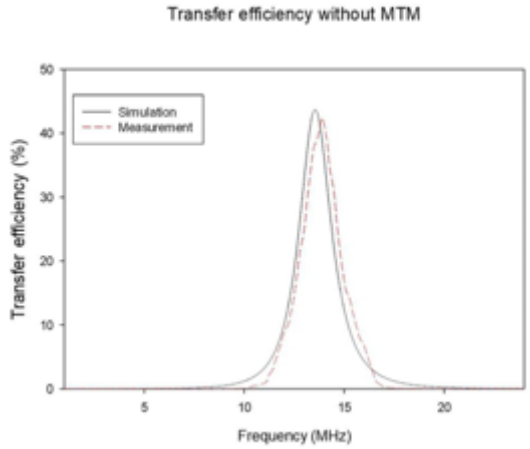


Fig. 8. Transfer Efficiency between real and simulation of without MTM

The transfer efficiency of a antenna without any MTM at a distance of 40mm is illustrated in Figure 8, which serves to compare the simulations. The transfer efficiency dropped minimally, with the simulation indicating 43.7% and the measurement indicating 42.5%, indicating a difference of a 2.7% reduction. The difference of 2.5% is the consequence of a shift in the resonant frequency from 13.56MHz to 13.9MHz. Simulation and measurement findings may differ due to factors such as imperfect equipment conditions and tolerances in lumped elements.

The major gap in transfer efficiency between antenna with and without MTM shows the essential role of these materials in enhancing Wireless Power Transfer systems. The lower efficiency in the absence of MTMs underscores their significance for achieving optimal performance in WPT systems. The implementation of MTMs into the antenna design significantly enhances transfer efficiency, indicating their capacity to redefine the performance of WPT systems.

Figure 9 illustrates the transfer efficiency of an antenna utilising MTM Modified SSRR at a distance of 40 mm. Simulation data shows that the antenna has a transfer efficiency of 58.1%; however, actual tests indicate slightly lower efficiency of 57.01%, leading to a drop of 1.87%. The minimal difference in efficiency between simulations and measurements is anticipated due to various causes and underlying errors in experimental setups.

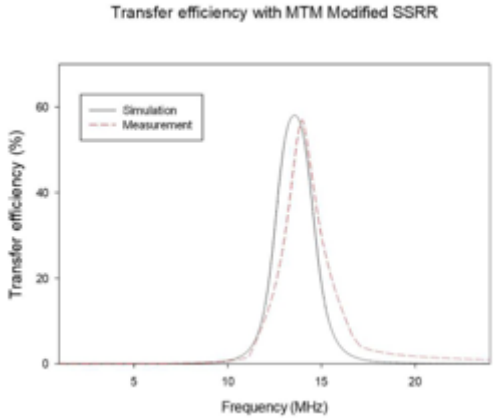


Fig. 9. Transfer Efficiency between real and simulation of with Modified SSRR

There was a 3.2% change in the resonance frequency of the system, from 13.56MHz to 13.995MHz. With these differences, Modified SSRR constantly shows high transfer efficiency in both simulated and actual testing settings. The minimal gap between simulation and measurement outcomes might come from experimental limitations or environmental factors not fully controlled in the simulation.

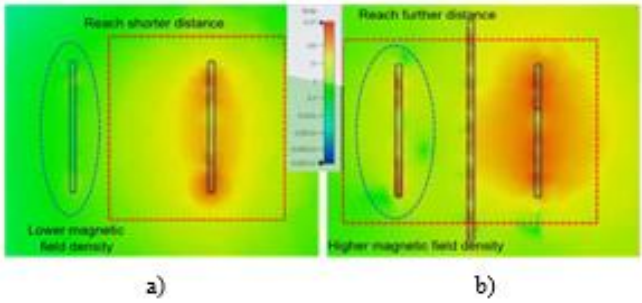


Fig. 10. Magnetic field of (a) WPT system without MTM and (b) WPT system with MTM

The WPT system configurations that have MTM integration and those that do not are simply defined in Figure 10. The presence of MTM leads to a significant increased concentration of the magnetic field, as evidenced by the intense

red colour, in contrast to the less distinct pattern seen without MTM. The obvious contrast clearly shows the essential role of MTM in boosting the flux density within the WPT system.

Additionally, the observed situations serve as evidence of the performance of MTM in modifying and redirecting the electric current paths to increase the induced current at the Rx. The inward refraction of flux direction toward the Rx region is amplified by the use of DNG-MTM topologies, which provides an optimal setting for efficient energy transmission.

MTM's role as a catalyst in enhancing transfer efficiency by directing good flow dynamics within the WPT system is verified by the data collected presented. The alteration of flux pathways by MTM represents significant progress in wireless energy transfer technology, indicating a dramatic shift towards new levels of performance and effectiveness.

4. CONCLUSION

This study's findings suggest that the use of different MTM designs can significantly boost the efficiency of resonant energy transfer in WPT systems. The simulation results reveal that the insertion of MTM-SSRR and MTM- modified SSRR structures between the transmitting and receiving antennas results in a substantial enhancement of the coupling coefficient between the resonators in comparison with the systems without MTMs. The results point to the potential of MTMs to enhance WPT systems and underline the need for more study on optimum MTM configurations. The architecture described here focuses on magnetic resonant coupling, although the principles covered here should be broadly applicable to systems employing evanescent wave coupling and potentially even to electrically coupled systems. The research shows significant improvements in PTE for near- field WPT systems, but it also highlights the need to evaluate the relevance of the design in practical and large-scale deployments. The integration of DNG-MTMs has good scalability potential, since their unique electromagnetic properties can be tailored for larger distances and higher power levels. However, practical challenges such as the cost of materials, complexity of manufacturing, and uniformity of MTM operation over large areas must be overcome to ensure the applicability of the system in real environments. These factors will be investigated in the future studies by testing the MTM- based WPT system for bigger scale applications such as electric autos and industrial applications.

Optimizations of MTM designs will be investigated to allow for larger power transfer ranges while maintaining efficiency. A full analysis on the scalability of the design will be given highlighting alternate options and further research needed to enhance the practicality and durability of the proposed WPT system for larger applications. The MTM-modified SSRR gives the most performance increases among the configurations tested, owing to its double-negative features. It is a good candidate for WPT applications owing to its robustness to high transfer efficiency across varying distances, where stable performance in different operating conditions is important. With increasing misalignment between the transmitter and receiver, systems with MTM have better PTE than systems without MTM, even with significant lateral and rotational misalignments.

The small dimensions of the MTM boost the system efficiency and space conservation, making it suitable for practical applications. The results highlight the potential of advanced MTM designs for upgrading WPT systems, opening up the path towards more efficient and flexible energy transfer technologies. Continuous research of the MTM development is important to realize their full potential for wireless power transmission applications.

ACKNOWLEDGEMENT

The author would like to acknowledge that this work is supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme FRGS (FRGS/1/2024/TK02/UTHM/03/4) and Universiti Tun Hussein Onn Malaysia (UTHM).

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