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Improving the Performance of a Wireless Power Transfer with Misalignment Using Magnetic Resonators Coil and Metamaterial Slabs

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ABSTRACT: The misalignment between the transmitter and receiver coils in the wireless power transfer WPT systems causes a reduction in the power transfer efficiency (PTE). This manuscript presents a numerical and experimental study of a WPT with different sequences that compensate for the misalignment effects of WPT systems. Circular loops were used for the transmitter's source coil and receiver's load coil. Then, a magnetic resonator coil has been added to the transmitter and receiver circular loops. The transmitter coil (Tx) has 4 turns and is connected to a 67 pF capacitor, and the receiver coil (Rx) has 14 turns and is connected to a 9 pF capacitor, which resonates at 13 MHz. The planner 5×5 spiral rings array of the metamaterial (MTM) was designed. The MTM unit cell has 5 turns and is loaded with an external 100 pF capacitor. Four scenarios are studied. The first one is the Tx and Rx coils in misalignment without MTMs, and the second one is by inserting the MTM plate in the middle space. Then, double plates are used in the middle, and finally, MTM plates are located behind the coils directly. The transmission coefficient S_{21} is enhanced by -7 dB when the MTM plate is placed in the middle space between coils. Adding another layer of MTM results in an increase in coupling between coils and enhances the S_{21} by -1 dB from the previous value. The PTE is improved from 32% to 63% in the instance of misalignment when MTM plates are behind coils. Finally, measurements are achieved and show acceptable agreement with the simulated results. This work could be helpful in biomedical implants where the locations of Tx and Rx coils are frequently changed.

1. INTRODUCTION

The technology of wireless power transfer (WPT) allows the power to be transmitted without cables [1]. The widespread use of mobile devices, including smartwatches, smartphones, and other wearables, continues to rise [2]. WPT aids in developing electronic and electrical systems that are streamlined, visually appealing, and practical. In recent years, electric vehicles have become more popular, which has helped lower greenhouse gas emissions and advance greener business [3–5]. Furthermore, the WPT possesses significant potential for application in space satellites, implantable devices, and various other uses [6–9].

Due to their extraordinary qualities, MTMs and metasurfaces (MSs) have recently gained significant attention in WPT [10–13]. As widely reported in the literature, these materials are artificial, do not exist naturally, and exhibit exceptional electromagnetic properties such as negative refractive index ($n < 0$) and negative permittivity and permeability ($\mu < 0$ and $\epsilon < 0$). These effective parameters can be modified by describing the form and behavior of the unit cell resonators that make up the specific meta-structure [14–16]. MTMs are typically formed by arranging resonant unit cells in a regular pattern, such as split-ring resonators and spirals. These unit cells must have dimensions smaller than the wavelength of incident waves and can be organized in either a three-dimensional or two-dimensional array. MTMs perceive electromagnetic waves as being composed of identical materials, disregarding their lattice structure [17–20]. Their ability to exhibit excellent electromagnetic characteristics across a wide frequency range, from RF to optical, has proven highly advantageous in various applications like electromagnetic absorbers, frequency-selective surfaces, biological applications, and lenses [21–24]. In particular, magnetic MTMs have been exploited to enhance the efficiency in wireless power transfer (WPT). Recently, there has been a surge in interest in the research of WPT due to the desire to eliminate the need for transmission lines in electronic equipment. This technique enables the transmission of a significant magnitude of power from a transmitting coil to a receiving coil, although certain limitations must be confronted [25–30]. The system's efficiency is highly contingent upon the coupling coefficient, which represents the level of interaction between the source and receiving coils. To optimize the coupling coefficient, it is necessary to position the two coils to ensure alignment, allowing most of the source's magnetic flux to pass to the receiver. Moreover, a significant issue when working in a near-field system is the rapid decline of the value of the magnetic field, which is directly proportional to the cube value of the distance. For these reasons, significant effort has been made to construct MTMs capable of improving the performance of wireless power transmission systems. Various studies

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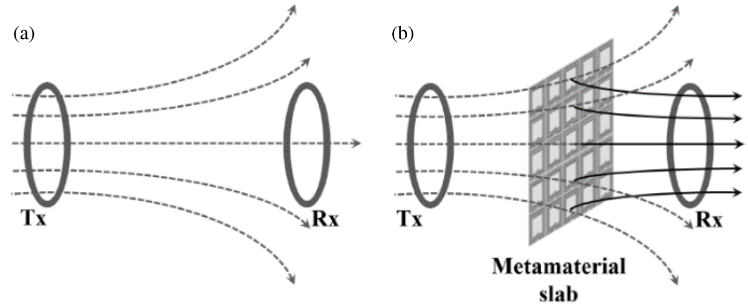

FIGURE 1. The basic concept of the WPT system with metamaterial. (a) WPT without MTM, (b) WPT with MTM.

have demonstrated that MTMs and metasurfaces (MSs) possessing negative magnetic permeability can function as guides to magnetic flux. They can concentrate and improve rapidly diminishing waves, enhancing WPT efficiency [31–37]. In the literature, researchers have studied different configurations and shapes of resonant helices and other unit cells to prove how MTM can improve the interaction of magnetic dipoles. Therefore, the distance between transmitting and receiving coils, misalignment robustness, and power transfer efficiency through an inductive link can be significantly enhanced [38–47]. In [48–50], it was also demonstrated that MTM can be used to reduce peaks in the electric field, hence achieving a higher safety level for the wireless power transfer system. This also ensures a higher degree of efficiency for power transfer than a traditional (driver-receiver) system. Specifically, when the system works within a range of a few megahertz, as is common in many wireless power transfer applications [51–54], it is essential to consider the strength of the electric field generated by the resonant coils. This contribution to the overall power capacity in the biological tissues should not be overlooked or carefully evaluated. Therefore, researchers face the challenge of finding suitable remedies to minimize the overall electric field without compromising the magnetic field distribution. This is crucial for preventing performance decay in wireless power transfer. The studies conducted in [55–59] showed that using metamaterials may effectively focus the magnetic field between coils of Tx and Rx, resulting in improved power transfer efficiency.

Figures 1(a) and (b) show the WPT without and with MTM, respectively. Utilizing an MTM slab, which has a negative refractive coefficient, amplifies evanescent waves and enhances the coupling coefficient between two coils.

This paper presents an experimental and numerical study to improve the efficiency of a WPT system by optimizing the positions of magnetic MTM plates in the whole WPT system. The MTM is fabricated on a thin layer of FR-4 material. In different positions, single and double layers of MTM plates are used to mitigate the effects of misalignment between transmitter (Tx) and receiver (Rx) coils. The magnetic field is enhanced and focused towards the receiver, and the transmission coefficients are also improved.

2. WPT WITH AND WITHOUT METAMATERIAL AND EQUIVALENT CIRCUITS

As stated in the Introduction, the objective of this research is to explain the capability to enhance the misalignment performance of a WPT system by optimizing the position of the magnetic metamaterial plates that are capable of homogenizing the distribution of the magnetic field generated by a source coil placed in the near field. Fig. 2 shows the equivalent circuit for this study's wireless power transmission system designs. A graphical depiction of the equivalent circuit describes the situations in which the WPT analysis was adopted. The circle loops, magnetic resonance coils, and MTM slabs can be modeled by an RLC series as shown in Fig. 2. The Tx and Rx coils with MTM are characterized by an RLC model circuit. Driver coil is described as R_D, L_D, and C_D, while the MTM slab is defined as R_1, R_2, L_1, L_2, and C_1, C_2. The receiver coil is described as R_R, L_R, and C_R, and the load loop is defined as R_L, L_L, and C_L.

The following analysis will analyze a basic two-coil magnetically coupled resonant wireless power transfer (MCR-WPT) system utilizing principles of equivalent circuit theory, which depend on the principles of Kirchhoff's laws and mutual inductance to establish a circuit model connecting the transmitting and receiving coils. This model, shown in Fig. 2, is used to determine equivalent relations and solve the system.

Applying Kirchhoff's principles allows us to get the equations for the voltage and current of the system, as demonstrated below:

$$\begin{matrix} Vs \\ 0 \\ 0 \\ . \\ . \\ . \\ 0 \end{matrix} = \begin{matrix} RS+ZDjwMDTjwMD1 & . & . & . & jwMDL \\ jwMDTZTjwMT1 & . & . & . & jwMTL \\ jwMD1jwMT1Z1 & . & . & . & jwM1L \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ jwMDLjwMTLjwM1L & . & . & . & RL+ZL \end{matrix} \begin{matrix} Id \\ IT \\ I1 \\ . \\ . \\ . \\ IL \end{matrix} \quad (1)$$

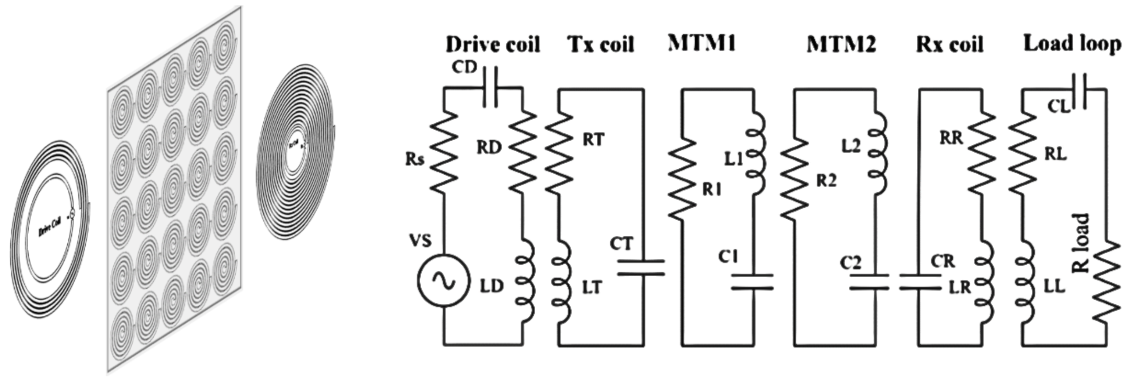

FIGURE 2. The WPT system with equivalent circuit: resonance coils and metamaterial.

TABLE 1. The parameters of the proposed design.

variables	Tx coil	Rx coil	Unit cell
External diameter	90 mm	100 mm	11.68 mm
Internal diameter	70 mm	30 mm	1.68 mm
Number of turns	4	14	5
Inductance	$L_t = 2.23\,\mu\text{H}$	$L_R = 12.1\,\mu\text{H}$	$L_1 = L_2 = 0.13\,\mu\text{H}$
Capacitance	67 pF	9 pF	100 pF
Resonance frequency	13 MHz	13 MHz	13 MHz

$$\begin{aligned}
Z_d &= R_d + j\left(wL_d - \frac{1}{WC_{di}}\right)\\
Z_T &= R_T + j(wL_T - \frac{1}{wC_{Ti}})\\
Z_i &= R_i + j\left(wL_i - \frac{1}{wC_{ii}}\right)\\
Z_R &= R_r + j\left(wL_r - \frac{1}{wC_{Ri}}\right)\\
Z_L &= R_L + j\left(wL_L - \frac{1}{wC_{Li}}\right)
\end{aligned} \tag{2}$$

$$S_{21} = 2\frac{V_L}{V_S}\sqrt{\frac{R_s}{R_L}} \tag{3}$$

The efficiency of the WPT system can be determined from the equation of transmission coefficient (S_{21})

$$PTE = |S_{21}|^2$$

3. DESIGN AND SIMULATION OF THE WPT WITH MTM

The proposed design comprises a source coil, transmitter (Tx), receiver (Rx), load coil, and MTMs. The structures of all coils are circular resonator coils due to their commonality in many applications. At resonance, the electromagnetic (EM) fields are concentrated within the resonators. The electromagnetic fields outside resonators attenuate exponentially and do not propagate power. Utilizing the MTM slab, which has a negative refractive coefficient, leads to the amplification of evanescent waves and the enhancement of the coupling coefficient between two coils. Fig. 3 shows the proposed design of two coils in misalignment, without and with metamaterial plate(s), in different locations, which is employed to manipulate the orientation of the EM field in the system in order to amplify the power transfer efficiency (PTE). When the MTM operates at a different frequency, the driver, Tx, Rx, and load coils must be set to operate at the same frequency as the MTM.

Table 1 shows dimensions, values of capacitances and inductances of all coils in the suggested design, as well as all other parameters.

The number of turns for the Tx coil is $N_1 = 4$, and the external diameter is 90 mm. The turns of the Rx coil are $N_2 = 14$, with an external diameter of 100 mm, located 30 mm above the Tx coil. The MTM layer is excited through the source near field, which varies from the excitation of a plane wave. So, we proposed 5×5 unit cells of MTM with an overall size equal to $168.67 \times 168.67\,\text{mm}^2$. Each cell is constructed from a 5-turn resonator, and the distance between cells is 1 mm. The MTM is located 5 mm above the Tx coil and 30 mm below the Rx coil, and another layer of MTM in the middle space has the exact dimensions as the first layer, with a separated distance of 17 mm between them. For more improvement in the PTE, we are moving the MTMs behind the Tx and Rx coils, with the separated distance between Rx and MTM1 and Tx and MTM2 being 15 mm and 17 mm, respectively.

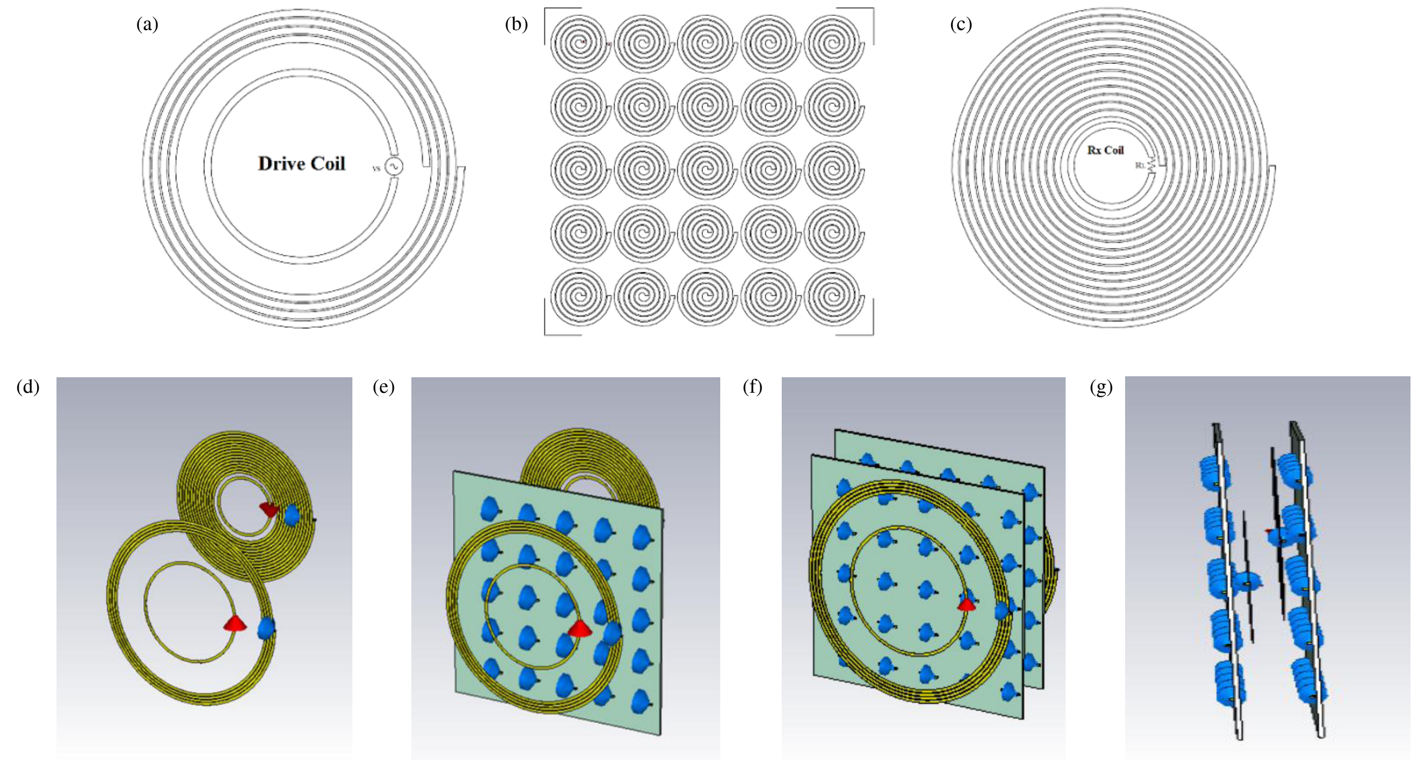

FIGURE 3. (a) Driving coil with Tx. (b) Front view of 5×5 MTM. (c) Load coil with Rx. (d) Side view of Tx and Rx coils. (e) Tx and Rx coils with one slab of MTM. (f) Double layer of MTM in the middle space. (g) Two plates of MTM placed behind the coils.

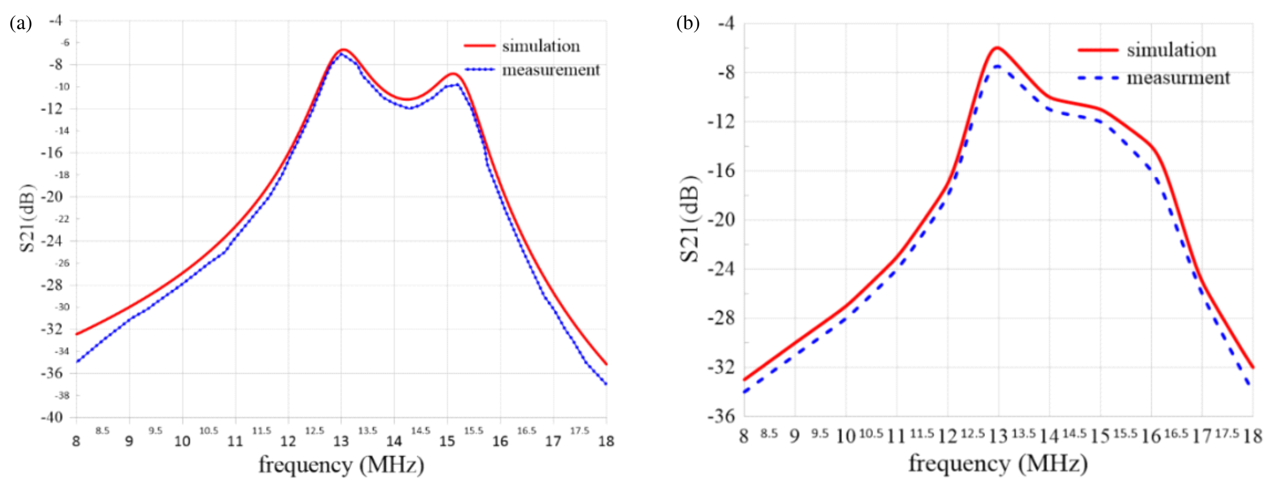

FIGURE 4. (a) The transmission coefficient of Tx, Rx coils without MTM. (b) S_{21} for center-to-center coils with MTM.

4. RESULTS AND DISCUSSION

In this section, the obtained results. when there is no misalignment between the coils, before adding the metamaterial layer, have been discussed. Then, the effect of the MTM on the electromagnetic field is studied. In the first step, a simulation of two coils, a transmitter, and a receiver was carried out in center-to-center mode without MTM to study the performance of a wireless power transmission system operating at a resonant frequency of 13 MHz. Figs. 4(a) and (b) show the S_{21} of transmitting and receiving coils, one placed precisely in front of the other.

From Fig. 4(a) it is noticed that the value of S_{21} is -7 dB at 13 MHz, and the separated distance between coils is 35 mm, so when using the MTM slab in the middle space between coils, the S_{21} reaches -6 dB at the same resonance frequency as mentioned in Fig. 4(b). As a result of adding the MTM layer, the coupling between the coils has increased. To understand the behavior of the metamaterial slab, we worked a vertical mismatch between the two coils at different distances and noticed that when the distance of mismatch increased, the less power was sent, thus the efficiency of the system decreased, and vice versa, Fig. 5(a) shows S_{21} for the cases mentioned above at

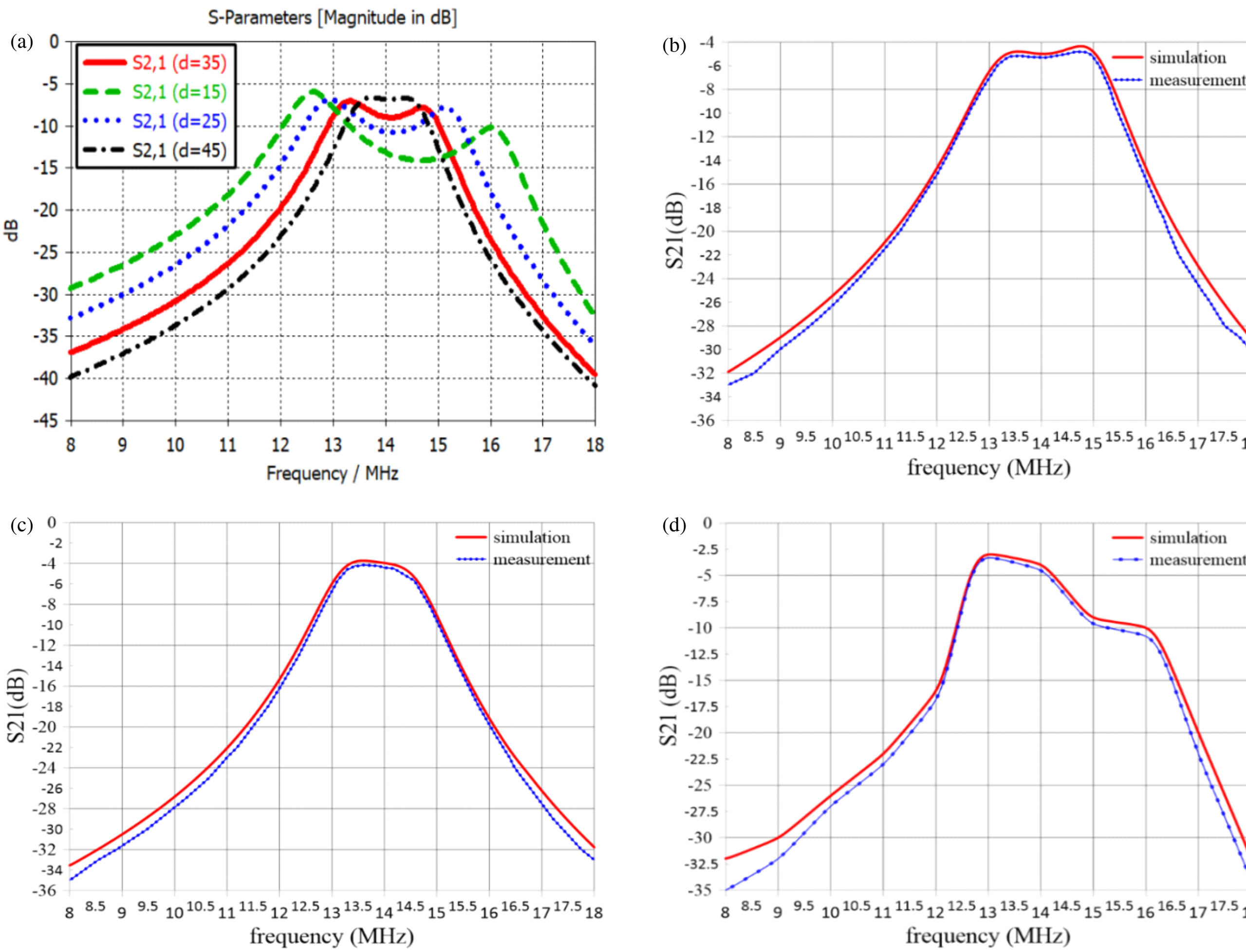

FIGURE 5. (a) S_{21} at different misalignment distances. (b) S_{21} with MTM at misalignment. (c) S_{21} with double layer of MTM. (d) S_{21} with MTM behind the coils.

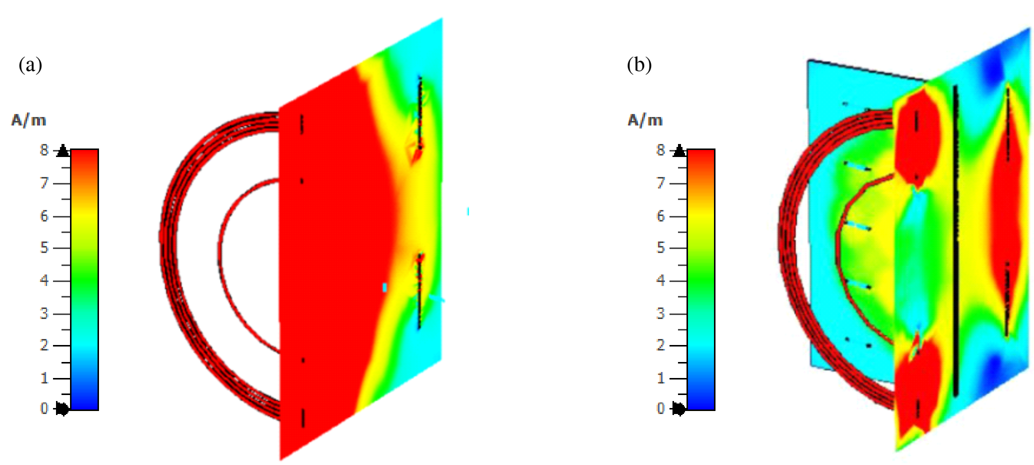

FIGURE 6. The magnetic field of Tx, Rx coils without misalignment. (a) Without MTM. (b) With MTM.

d = 15, 25, 35, and 45 mm (where d = the vertical misalignment distance). To improve the transmission coefficient during misalignment between the Tx and Rx, the MTM plate is added in the middle space between mismatch coils, and the scattering parameter S_{21} is increased by -7 dB as shown in Fig. 5(b). To further improve the power transmission efficiency PTE, another layer of the MTM was inserted close to the first layer, and as a result of increasing the coupling between the coils and plates, the S_{21} was enhanced as shown in Fig. 5(c). More enhancement in S_{21} is achieved when MTM plates are located directly behind the coils, as shown in Fig. 5(d).

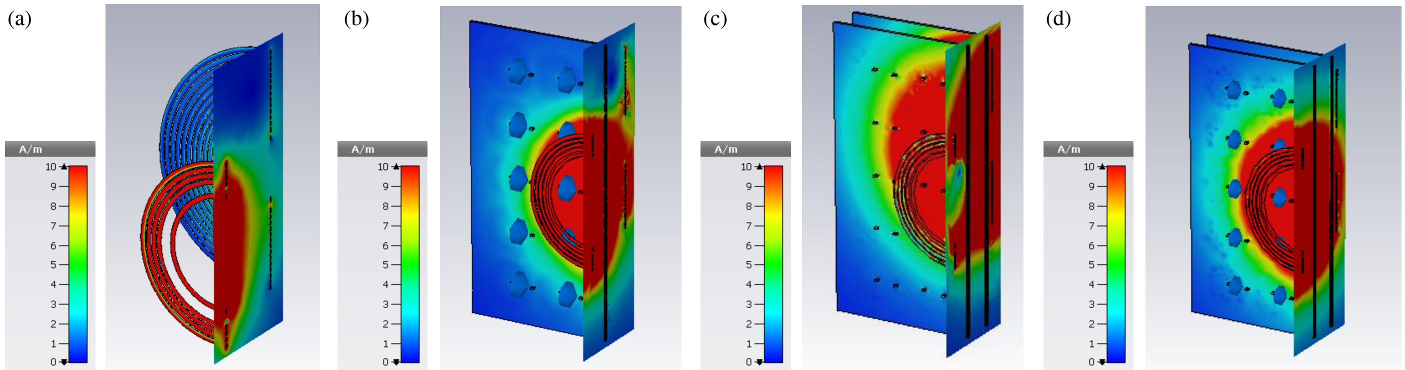

FIGURE 7. The magnetic field of Tx and Rx with vertical misalignment. (a) Without MTM. (b) With one layer of MTM. (c) With double slabs of MTM in the middle. (d) With two plates of MTM behind the coils.

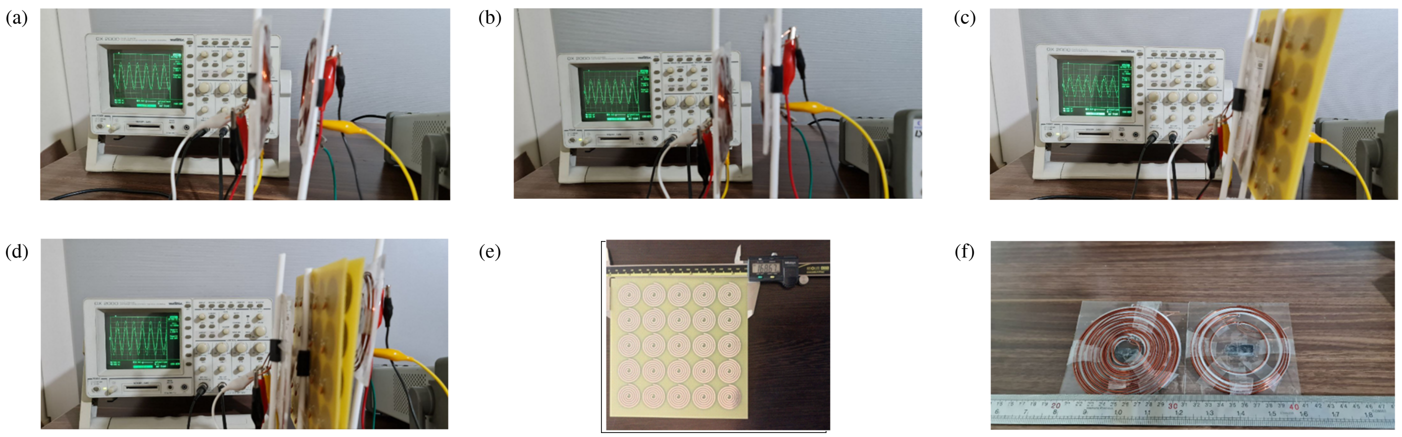

FIGURE 8. The fabrication and experimental results. (a) The proposed two coils center-to-center. (b) The Tx and Rx coils with misalignment. (c) The fabricated MTM placed between coils. (d) The fabricated double MTM plates. (e) The dimensions of the MTM. (f) The dimensions of the Tx and Rx coils.

Figures 6(a) and (b) display the distribution of the magnetic field intensity for the WPT system center-to-center with and without the MTM layer. Figs. 7(a), (b), (c), and (d) present the magnetic field during vertical misalignment between the Tx and Rx coils before and after adding the MTM slab. The magnetic field produced by the transmitter coil is refocused through the MTM layer, resulting in an increased magnetic field strength at the receiver coil, which enhances the system's power transfer efficiency.

5. FABRICATION AND MEASUREMENT RESULTS

The proposed WPT system with double plates of MTM was fabricated using the instructions in Fig. 3 to verify the simulated results. The design consisted of a source coil, Tx, Rx, and load coil fabricated from copper. The MTM was built on a thin substrate layer of FR-4 material. External capacitors were added to the Tx, Rx, and MTM unit cells to tune a resonance frequency of 13 MHz. The measurement results were compared with the simulations in CST Studio Suite. The results showed an acceptable agreement between the measurement and simulation. Fig. 8 shows the experiment setup of the proposed design.

6. CONCLUSION

This article presents a numerical and experimental study of different sequences of a wireless power transmission system that consists of Tx and Rx coils supported by MTM slab(s) with spiral resonators to improve the efficiency and reduce the misalignment effect between the transmitter (Tx) and receiver (Rx). In the case of a misalignment between Tx and Rx coils, the transmission efficiency is reduced. So by using MTM layer(s) in such a system, this reduction in efficiency is compensated. When the MTM layer is placed in the middle distance between coils, the transmission coefficient S_{21} is improved by -7 dB. The MTM slab was duplicated in the middle space, which led to an increase in the coupling and thus improved the S_{21} by -1 dB compared with a single layer. The efficiency was increased from 32% to 63% when the MTM plates were moved behind the Tx and Rx coils, and the S_{21} increased by -2.5 dB. The magnetic field is also analyzed and noticed while inserting the 5×5 MTM slab, refocusing the magnetic field in the direction of the receiving coil, and a reducing the percentage of magnetic field loss, especially when using MTM slabs behind coils (Tx and Rx). The proposed wireless power transfer system design with MTM was fabricated and compared with the simulated results. The experimental and simulated results showed acceptable agreement, demonstrating the effectiveness of the suggested design. This design is suitable for the use in modern electronic systems such as implantable medical apparatus and other different applications.

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