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Efficiency Enhancement of Wireless Power Transfer System Using MNZ Metamaterials

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Abstract—In this paper, a simple approach for efficiency enhancement of a wireless power transfer system by using mu near zero (MNZ) type of metamaterial is proposed. A single slab containing one-sided periodic structures of 3×3 array of meander-line unit cell has been placed between transmitting and receiving coils in the wireless power transfer system. The presented metamaterial structure is less complex than other reported metamaterial structures in the area of wireless power transfer system. The simulation and measurement have been performed with and without the metamaterial slab. Using the metamaterial slab, the maximum efficiency has been obtained about 55.3%, i.e., an improvement of efficiency around 15.7% is obtained compared to a wireless power transfer system without the metamaterials. Interestingly, the proposed wireless power transfer system shows a steady improvement of efficiency even if the distance between the transmitting and receiving coil is increased.

1. INTRODUCTION

Wireless Power Transfer (WPT) is an efficient approach for the transmission of electric power from one place to another through atmosphere without any physical link or contact. The concept of WPT was first proposed and demonstrated by Nikola Tesla in his pioneer work [1]. There has been increasing interest in the research and development of WPT, due to its wide applications in portable devices such as mobile phone charging [2], laptop charging [3], automatic guided vehicles and robots [4], etc. Also, in the sector of biomedical applications, WPT is in very high demand such as data telemetry for retinal prosthesis [5], micro-robot endoscopy [6], magnetic resonance imaging (MRI) [7], etc. Therefore, WPT has a promising future in several fronts having different power level operations varying from milliwatt in the case of biomedical applications to kilowatt units in the case of automobiles. WPT has also been applied over different distances ranging from millimetre to as large as metres.

Depending upon the application requirement, a WPT system can be divided into three possible categories: inductive coupling, resonant coupling and microwave power transmission. Inductive coupling and resonant coupling are used in short-range applications, and microwave power transmission system for long-range applications. In inductive coupling [2, 4–6], good mutual inductances among the coils are required, which depend upon quality factor (Q) and coupling coefficient (k) among the coils. A high value of coupling coefficient ($k > 0.9$) and precise orientation of the coils are necessary for efficient power transfer [8]. In this system, the efficiency is limited by the quality factor of the coils and the mutual coupling between the coils. The mutual coupling decreases rapidly due to increasing distance between the coils. In [9], it was first reported that magnetic resonant coupling using a non-radiative mid-range field was used for wireless power transfer, and the authors of [9] were able to transfer high efficiency power over the distance of two meters. After that, power transfer using magnetic resonance has drawn great attention by several authors [3, 7], mainly due to its ability of transmitting power with

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significant misalignment between coils, i.e., with low coupling coefficient ($k < 0.2$) [8]. For maximum power transmission, high Q-factors and essentially same resonant frequencies are required for both the transmitting (Tx) and receiving (Rx) coils. However, the main problems of this system are short range power transmission and low efficiency. In [10], a technique was reported to achieve higher efficiency and better range for WPT by connecting a parallel capacitor in both Tx and Rx ends of the coils.

In recent times, due to the unusual properties such as negative permittivity and/or negative permeability, metamaterial (MTM) has been widely used for performance enhancement of the WPT system. There are various literatures by several authors in the context of the WPT using metamaterial to increase the efficiency and range [11–18]. In [11], for the first time, the use of MTM in the field of the WPT was introduced by using negative index MTM for the enhancement of the coupling coefficient and the transfer efficiency. In [12], a rigorous theoretical analysis was presented for enhancement of WPT by using metamaterial slab. In [13], Wang et al. proposed the use of magnetic metamaterials to enhance the evanescent wave coupling and improve the transfer efficiency of the wireless power transfer system based on coupled resonators. Also, an efficient wireless power transfer system by using highly sub-wavelength negative refractive index (NRI) and negative permeability (MNG) metamaterial has been designed in [14]. Another technique for improving power transfer efficiency of a short-range telemetry system using compact magnetic metamaterial has been reported in [15]. In [16], an efficient wireless power transfer has been achieved by using modified mu-zero resonator (MZR), which provides stronger coupling than the other modes. In [17], with the help of zero refractive index property of the MTM, a highly efficient WPT system has also been reported. Very recently in [18], a ferrite loaded solenoid three-dimensional (3-D) MTM unit cell at low-frequency was designed for efficiency enhancement of WPT system. In [13, 18], the efficiency enhancement of WPT system has been achieved, but the proposed MTM unit cell structures are 3-D, and as a result, the system becomes complex and bulky. In [14], two different MTM unit cell structures were printed on the both sides of the dielectric to obtain negative refractive index property of MTM, which is a little bit complicated to design. In [15], multilayer metamaterial slabs have been placed between Tx and Rx coils, which increases the overall size of the WPT system. In [16, 17], both sides with printed MTM unit cell has been used for WPT system, which increases the design complexity.

In this paper, we propose a simple technique for efficiency enhancement of WPT system by using MNZ type of metamaterial. Here the MTM slab is designed from electric (ELC) resonator. The MTM unit cell is composed of a meander-line structure designed on a single side of dielectric instead of a double-sided structure. A single slab of an array of 3×3 one-sided periodic structures of a meander-line unit cell has been placed between the transmitting and receiving coils in the WPT set up for efficiency enhancement. The MNZ as well as low loss behaviour of the MTM structure results in the enhancement of power transfer efficiency by providing strong coupling between the coils. The simulation and measurement have been done with and without the MTM structure. With the help of the metamaterial placed in between Tx and Rx coils, the maximum efficiency is obtained about 55.3%. An improvement of efficiency around 15.7% is achieved.

2. CONFIGURATION AND CHARACTERIZATION OF METAMATERIAL SLAB

In the proposed WPT system, we use the MNZ property of the metamaterial, which is obtained from a MTM resonator having ELC behaviour. The MTM unit cell consists with the help of meander-line structure designed on the single side of dielectric which eliminates the fabrication difficulties as required in the case of double-sided structures. The schematic configuration of the MTM unit cell is shown in Figure 1. The MTM unit cell consists of a meander-line structure on single side of an FR4 dielectric which has a dielectric constant of 4.4, dielectric thickness of 1.6 mm, and loss tangent of 0.02. The presented MTM structure is mainly inspired from [19]. The dimension of the MTM unit cell ($Ls \times Ws$) is $60 \times 60\,\text{mm}^2$.

A normal incident plane wave having a polarized electric field in the x direction is considered for the calculation of the scattering parameters of the MTM unit cell structure. The reflection and transmission coefficients are obtained from a single unit cell with the use of periodic boundary conditions. The simulated S-parameter (S_{11} & S_{21}) plots of the unit cell are shown in Figure 2. It can be observed from Figure 2 that over the range of 20 MHz to 30 MHz, the MTM unit cell structure provides better

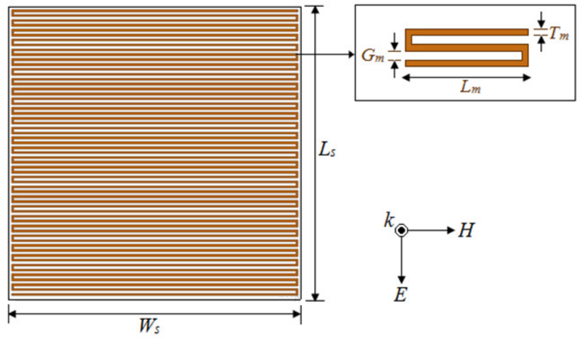


Figure 1. Schematic configuration of metamaterial unit cell. The meander line dimensions shown in inset are $L_m = 58.8\,\mathrm{mm}$, $T_m = 0.4\,\mathrm{mm}$, $G_m = 0.6\,\mathrm{mm}$.

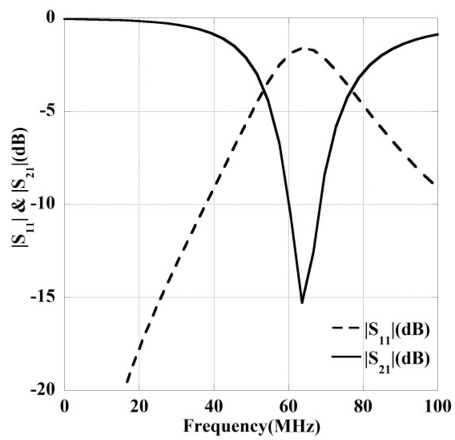


Figure 2. The simulated S_{11} and S_{21} plots of the MTM unit cell.

transmission of electromagnetic power and significantly low reflection coefficient. The extracted relative permittivity and permeability plots of the unit cell structure are shown in Figures 3(a) and 3(b), respectively. The MNZ behaviour of the MTM structure is observed over the range of frequency from Figure 3(b).

Generally, the loss in the metamaterial is represented by figure of merit (FOM). The FOM is defined as the ratio of the real and imaginary parts of refractive index (n), $|\mathrm{Re}(n)/\mathrm{Im}(n)|$, of a metamaterial unit cell. The FOM plot of the unit cell structure is shown in Figure 3(c). It is observed from the figure that in frequency range of 20 MHz to 30 MHz the value of FOM is quite high, which means that a low loss behavior exist in this range. The retrieval method based on Kramers-Kronig relationship [20] has been used for parameter extraction. The simulation of MTM unit cell has been done using the high-frequency structure simulator (HFSS). The MTM slab has been designed by an array of 3×3 unit cells with the dimension of $180 \times 180\,\mathrm{mm}^2$, which is used for improving efficiency of the WPT system in the next section.

3. SIMULATION AND EXPERIMENTAL SETUP OF PROPOSED WIRELESS POWER TRANSFER SYSTEM

The simulation of the WPT system with and without metamaterial is performed by COMSOL Multiphysics. In this paper, a four-coil based structure is proposed to design the WPT system, because multi-coil system provides high Q-factor and strong coupling for maximum power transmission [21]. This system consists of a transmitting loop antenna, a receiving loop antenna, a transmitting coil and a receiving coil. Power is directly fed to the transmitting loop antenna that has a radius (R_{loop}) of

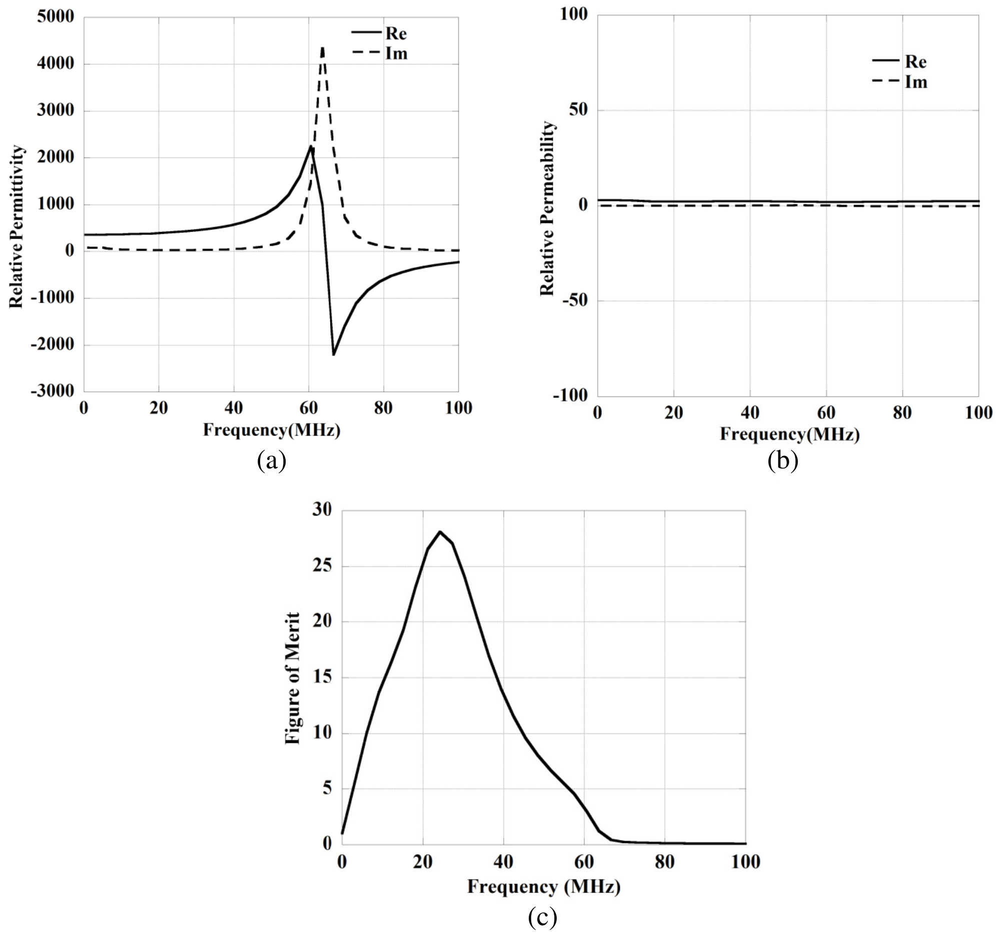


Figure 3. Extracted parameters. (a) Relative permittivity. (b) Relative permeability. (c) FOM vs Frequency plot of the MTM unit cell.

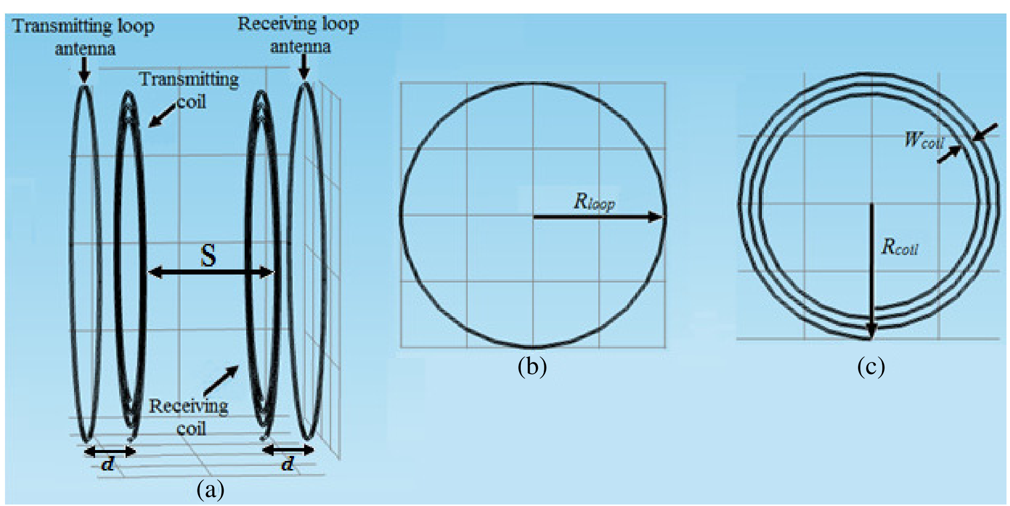
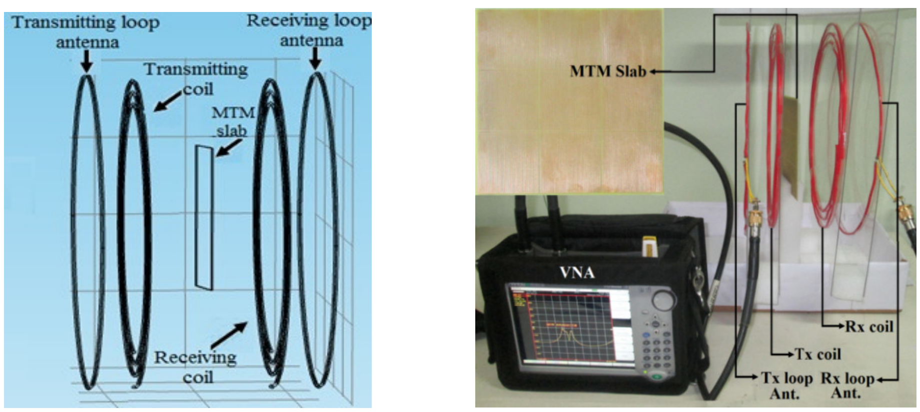


Figure 4. (a) Schematic of simulation setup with loop antennas and coils. (b) Schematic of transmitting and receiving loop antennas, $R_{\text{loop}} = 20\,\text{cm}$. (c) Schematic of transmitting and Receiving coils, $R_{\text{coil}} = 20\,\text{cm}$, $W_{\text{coil}} = 1.5\,\text{cm}$.

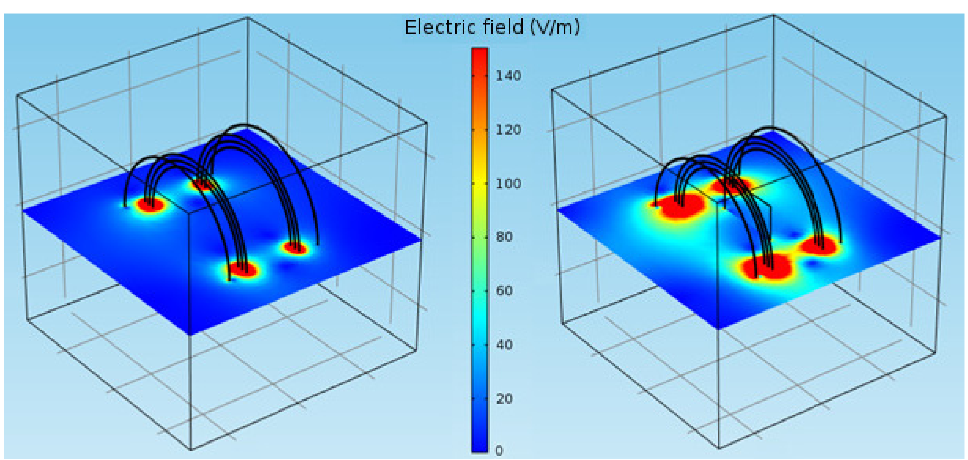
20 cm. It radiates power, and at resonant frequency maximum energy is radiated from the transmitting loop antenna. Subsequently maximum energy is stored in the near field of the transmitting antenna. This energy is magnetically coupled to the transmitting spiral coil that has 3 turns and outer radius of 20 cm with 1.5 cm radial pitch. This coil works as a resonator, and at the resonant frequency it stores the maximum amount of energy around it. This resonator structure plays a key role of transferring power to receiving system, and the entire coupling occurs magnetically. The power stored around the transmitting coil induces a voltage to the receiving coil which is obtained through the receiving loop antenna. The receiving antenna and coil both have the same dimensions corresponding to their transmitting counterpart. The schematic configurations used in the simulation are shown in Figure 4. In the first simulation, a variation of efficiency with frequency over different distances is performed. After that, an MTM slab is placed between the Tx and Rx coils, and the simulation setup of the WPT system is shown in Figure 5(a). The corresponding measurement setup is shown in Figure 5(b). The fabricated metamaterial prototype structure is shown in the inset of Figure 5(b).

Figure 6 shows the electric field distribution of the proposed WPT system for both with and without the MTM slab. It can be observed from the figure that without the MTM slab the electric field intensity in Figure 6(a) is quite low compared to that with MTM slab as shown in Figure 6(b). The



(a) (b)

Figure 5. The WPT system with MTM slab. (a) Schematic of simulation setup in COMSOL. (b) Measurement setup, in inset the fabricated structure of an array of 3×3 MTM slab is shown.



(a) (b)

Figure 6. Electric field distribution from COMSOL simulation. (a) Without MTM slab. (b) With MTM slab.

field simulation shows that the coupling can be enhanced between Tx and Rx coils with the MNZ as well as low loss MTM, and as a result of this the power transfer efficiency is improved.

The value of the transmission coefficient (S_{21}) is measured as the efficiency of the WPT is expressed as $|S_{21}|^2$ in [10, 13]. The coils are made according to the specification mentioned earlier used in simulation. The distance (d) between the loop antenna and coil is optimized at 5 cm to obtain the maximum power transfer efficiency. The distance (S) between the Tx and Rx coils is varied at 5 cm, 10 cm, 15 cm and 20 cm. For each measurement setup, the value of S_{21} is measured using Anritsu MS2025B vector network analyser (VNA) to obtain the efficiency of the system.

4. RESULTS AND DISCUSSIONS

Here, the simulated and measured efficiencies are observed over different frequencies and distances. Obviously, the efficiency will decrease with an increase in distance between the coils. However, the amount of improvement in efficiency with metamaterial slab for different distances is the major point of our observation. So, the frequency is varied over a range of 20 MHz to 30 MHz, setting the distances between the transmitting and receiving coils at 5 cm, 10 cm, 15 cm and 20 cm, respectively. Both the transmitter and receiver sides, the distance between the loop antenna and coil are kept at 5 cm. The maximum efficiency is observed when both coils are at minimum distance, i.e., 5 cm apart in this proposed design. Here without metamaterial, the maximum efficiencies of 42.3% and 39.6 % are obtained from simulation and measurement, respectively. After that, the metamaterial slab is placed between the coils and maximum efficiencies of 57.4% in the simulation and 55.3% in measurement are obtained. So, an improvement of efficiency around 15.7% is obtained using metamaterial in this case. Figures 7(a) and 7(b) show the simulated and measured efficiencies versus frequency plots for with and without MTM at 5 cm and 10 cm, respectively.

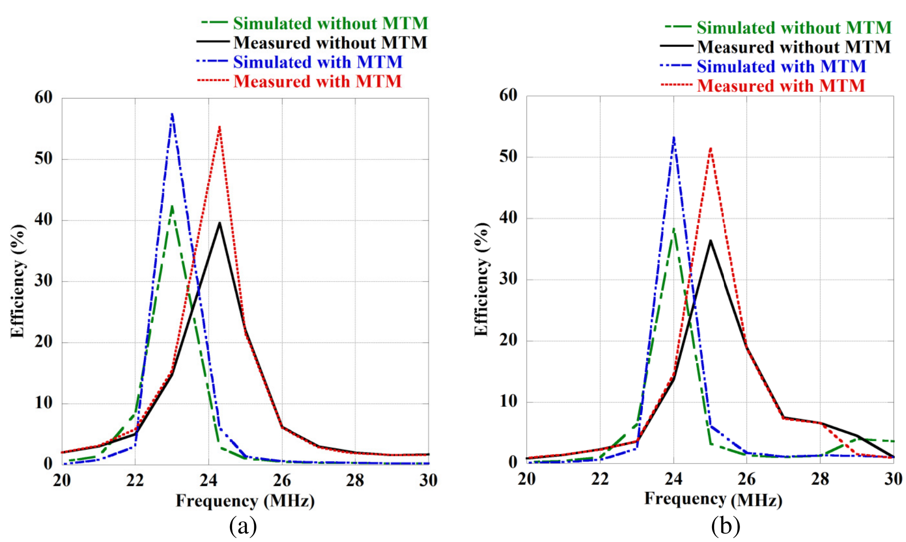


Figure 7. Plot of efficiency vs frequency at different distances between Tx and Rx coils. (a) 5 cm. (b) 10 cm.

Efficiency enhancement for different distances is obtained and summarised in Table 1. The graphical plot of efficiency against distance between Tx and Rx coils of the WPT system is shown in Figure 8. It can be observed from Figure 8 that by using MTM slab, a significant amount of efficiency enhancement is achieved. It is also noticed that the efficiency improvement remains steady even if the distance between the Tx and Rx coils is varied.

A comparison between the present proposed work and other reported WPT systems using an MTM structure is shown in Table 2. It can be pointed out from the table that the presented unit cell offers low design complexity compared to all other MTM unit cell structures used to enhance the efficiency

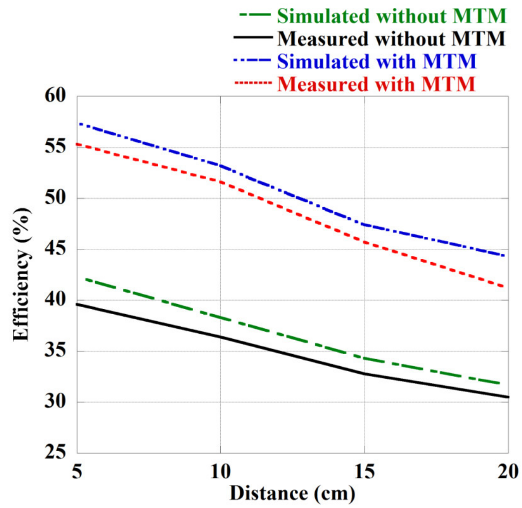


Figure 8. Plot of efficiency vs distance between Tx and Rx coils of the WPT system.

Table 1. Comparison of the different results obtained from the measurement during distance variation between Tx and Rx coils.

Distance between Tx & Rx coils (cm)	Operating frequency (MHz)	Efficiency without MTM (%)	Efficiency with MTM (%)	Efficiency enhancement (%)
5	24.3	39.6	55.3	15.7
10	25.0	36.4	51.6	15.2
15	26.2	32.8	45.7	12.9
20	27.4	30.5	41.2	10.7

Table 2. Comparison between the proposed work and other reported wireless power transfer system using metamaterial.

Reported WPT system	MTM unit cell type	Design configuration of unit cell	Design complexity of unit cell	Operating Frequency (MHz)	Distance Between Tx & Rx coils (cm)	Measured Efficiency (%)
J. H. Park, et al., 2014 [16]	Mu-zero resonator	Both sided structure	Moderate	14.2	5 10	69.3 19.7
H. Kim, et al., 2014 [17]	ZRI	Both sided structure	Moderate	6.78	10 15	54.4 45.2
E. S. G. Rodriguez, et al., 2016 [18]	Magnetic resonator	Three-dimensional (3-D)	High	5.57	4.5	35
Proposed Work	MNZ	Single sided structure	Low	24.3 25.0 26.2 27.4	5 10 15 20	55.3 51.6 45.7 41.2

of a WPT system. It is also observed that the measured WPT efficiency is better than than in [18]. Though in [16], the efficiency for shorter distance is better than the proposed work, but in the case of longer distances the proposed work is much better.

5. CONCLUSION

A simple approach for efficiency enhancement of the WPT system by using MNZ as well as low loss metamaterial is presented. The proposed setup has been built for WPT system using an MTM slab. In measurement, the efficiency is increased from 39.6% to 55.3% using an MTM slab, so around 15.7% improvement of efficiency is obtained compared to WPT without the MTM slab. It is noticed that the proposed WPT system shows a nearly steady improvement of efficiency even if the distance between the Tx and Rx coil is increased. The discrepancies between measured and simulated results are due to the conductive loss of wires and misalignment of coils in measurement setup.

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REFERENCES

1. Tesla, N., "Apparatus for transmitting electrical energy," US Patent, Serial No. 371817, 1–4, Dec. 1914.
2. Olvitz, L., D. Vinko, and T. Svedek, "Wireless power transfer for mobile phone charging device," *MIPRO, Proc. of the 35th International Convention*, 141–145, Opatija, Croatia, May 2012.
3. Nguyen, V. T., S. H. Kang, J. H. Choi, and C. W. Jung, "Magnetic resonance wireless power transfer using three-coil system with single planar receiver for laptop applications," *IEEE Tran. Consum. Electron.*, Vol. 61, No. 2, 160–166, May 2015.
4. Elliott, G. A. J., R. Stefan, G. A. Covic, and J. T. Boys, "Multiphase pickups for large lateral tolerance contactless power-transfer system," *IEEE Tran. Ind. Electron.*, Vol. 57, No. 5, 1590–1598, May 2010.
5. Wang, G., W. Liu, M. Sivaprakasam, M. Zhou, J. D. Weiland, and M. S. Humayun, "A dual band wireless power and data telemetry for retinal prosthesis," *Proc. IEEE EMBS Annual International Conference*, 4392–4395, New York City, USA, Aug.–Sep. 2006.
6. Yan, G., D. Ye, P. Zan, K. Wang, and G. Ma, "Micro-robot for endoscope based on wireless power transfer," *Proc. IEEE International Conference on Mechatron and Automat*, 3577–3581, Harbin, China, Aug. 2007.
7. Freire, M. J., R. Marques, and L. Jelinek, "Experimental demonstration of a $\mu = -1$ metamaterial lens for magnetic resonance imaging," *Appl. Phys. Lett.*, Vol. 93, 231108, 1–3, Dec. 2008.
8. Wang, B., W. Yerazunis, and K. H. Teo, "Wireless power transfer: metamaterials and array of coupled resonators," *Proc. IEEE*, Vol. 101, No. 6, 1359–1368, Jun. 2013.
9. Kurs, A., A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, Vol. 317, 83–86, Jul. 2007.
10. Kim, Y. and S. Lim, "Compact magnetic coupled resonator with high efficiency during misaligned wireless power transmission," *Journal of Electromagnetic Waves and Applications*, Vol. 27, No. 15, 1942–1948, Aug. 2013.
11. Wang, B., T. Nishino, and K. H. Teo, "Wireless power transmission efficiency enhancement with metamaterials," *Proc. IEEE International Conference on Wireless Information Technology and System (ICWITS)*, 1–4, Honululu, HI, USA, Sep. 2010.
12. Urzhumov, Y. and D. R. Smith, "Metamaterial-enhanced coupling between magnetic dipoles for efficient wireless power transfer," *Phys. Rev. B*, Vol. 83, 205114, 1–10, May 2011.

13. Wang, B., K. H. Teo, T. Nishino, W. Yerazunis, J. Barnwell, and J. Zhang, "Experiments on wireless power transfer with metamaterials," *Appl. Phys. Lett.*, Vol. 98, 254101, 1–3, Jun. 2011.
14. Fan, Y., L. Li, S. Yu, C. Zhu, and C. Liang, "Experimental study of efficient wireless power transfer system integrating with highly sub-wavelength metamaterials," *Progress In Electromagnetics Research*, Vol. 141, 769–784, Aug. 2013.
15. Rajagopalan, A., A. K. RamRakhyani, D. Schurig, and G. Lazzi, "Improving power transfer efficiency of a short-range telemetry system using compact metamaterials," *IEEE Tran. Microw. Theory Tech.*, Vol. 62, No. 4, 947–955, Apr. 2014.
16. Park, J. H., B. C. Park, Y. H. Ryu, E. S. Park, and J. H. Lee, "Modified mu-zero resonator for efficient wireless power transfer," *IET Microw. Ant. Propag.*, Vol. 8, No. 12, 912–920, Mar. 2014.
17. Kim, H. and C. Seo, "Highly efficient wireless power transfer using metamaterial slab with zero refractive property," *Electronics Lett.*, Vol. 50, No. 16, 1158–1160, Jul. 2014.
18. Rodriguez, E. S. G., A. K. Ram Rakhyani, D. Schurig, and G. Lazzi, "Compact low frequency metamaterial design for wireless power transfer efficiency enhancement," *IEEE Tran. Microw. Theory Techn.*, Vol. 64, No. 5, 1644–1654, May 2016.
19. Kolb, P. W., T. S. Salter, J. A. McGee, H. D. Drew, and W. J. Padilla, "Extreme subwave length electric GHz metamaterials," *J. Appl. Phys.*, Vol. 110, 054906, 1–5, Sep. 2011.
20. Szabo, Z., G. H. Park, R. Hedge, and E. P. Li, "A unique extraction of metamaterial parameters based on Kramers-Kronig relationship," *IEEE Trans. Microw. Theory Tech.*, Vol. 58, No. 10, 2646–2653, Oct. 2010.
21. RamRakhyani, A. K. and G. Lazzi, "On the design of efficient multi-coil telemetry system for biomedical implant," *IEEE Tran. Biomedical Circuits Sys.*, Vol. 7, No. 1, 11–23, Feb. 2013.