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Review

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Applications of negative permeability metamaterials for electromagnetic resonance type wireless power transfer systems

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Abstract. With the development of electric drive systems such as unmanned aerial vehicles and electric vehicles, the charging problem of power supply devices has become increasingly prominent. However, the traditional charging method requires physical circuits, which makes it impossible to achieve freedom of the position in actual use. The wireless power transmission technology, which mainly relies on electromagnetic wave to complete energy transmission, is expected to get rid of the restriction of physical space location and solve the problem of charging location, which has great potential in medical treatment, rescue, detection and other fields. However, the low transmission efficiency and short transmission distance caused by electromagnetic field leakage are the two main problems faced by radio energy transmission systems. In general, with the increase of transmission distance, the transmission efficiency will drop sharply. Fortunately, inserting a negative permeability metamaterial with extraordinary electromagnetic characteristics into the transmitting and receiving coils will greatly alleviate this attenuation trend and can also shield electromagnetic radiation to a certain extent. In this paper, some experiments of negative permeability metamaterials used in electromagnetic resonance type wireless power transfer systems are summarized for reference.

Keywords: Wireless power transfer / negative permeability metamaterial / electromagnetic resonance type / transmission efficiency / electromagnetic field leakage

1 Introduction

With the continuous development of society and technology, the daily use of mobile devices, such as mobile phones, tablets, laptops and so on, has become more common and accessible, so the requirements for charging have dramatically increased. Compared with traditional wired charging, wireless charging may become a more convenient way to meet the "mobile" needs. Since the charging plug does not need to be connected during charging, the wear of the charging system will also be reduced, which is very helpful for improved safety. Wireless charging is usually based on wireless power transfer (WPT) technology. This technology was firstly proposed by Nicholas Tesla [1]. It has been a hundred years since now. Researchers have proposed electromagnetic induction [2], electromagnetic resonance [3] and electromagnetic radiation [4]. The three transmission modes have their own characteristics and advantages, as shown in Table 1.

The electromagnetic resonance type wireless power transfer system is mainly composed of the transmitting end, the load end and the control circuit, in which the principle is the energy coupling between the transmitting end and the load end as shown in Figure 1 [5]. Since the WPT system of transmission mode has moderate transmission distance and appropriate efficiency, it becomes potentially more practical. For example, the WPT system has applications in implantable medical devices [6–8], unmanned aerial vehicles [9–11], the internet of things [12] and other fields. At present, transmission efficiency and transmission distance are two main aspects of WPT system that need to be improved, and they are mutually exclusive. However, there it is difficult to fully consider them, and we should make compromises based on the actual applications. EMF leakage is related to the actual use safety of the WPT system [13]. The main factors affecting the transmission efficiency are the coupling coefficient between the power transmission coils, the coil quality factor and the load. Among them, the coupling coefficient is one of the main research directions at present. Coils with high permeability materials, like ferrite cores, are used to improve magnetic coupling. However, a demagnetization field is inevitably generated during the magnetization process, and to reduce the effect of demagnetization, a larger volume of ferrite cores is required, which limits practical applications.

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Table 1. Three modes of WPT system transmission.

Transmission mode	Transmission distance	Transmission efficiency
Electromagnetic induction type	Close distance (<10 cm)	High
Electromagnetic resonance type	Medium distance (<10 m)	Medium
Electromagnetic radiation type	Long distance (within thousands of meters)	Low

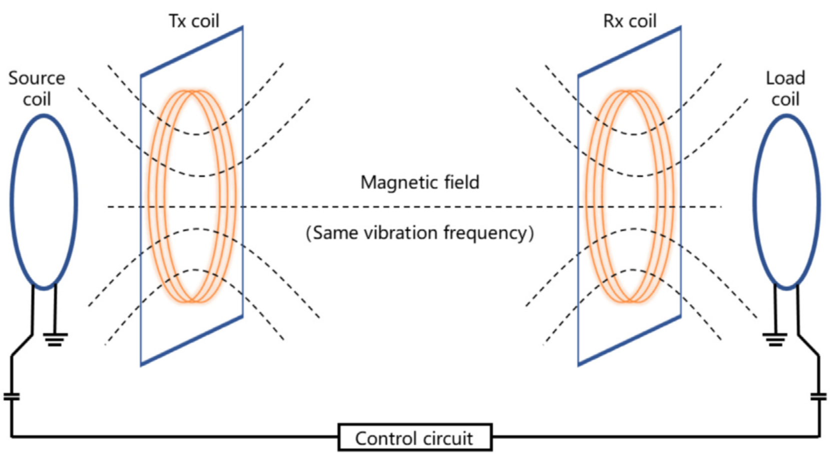

Fig. 1. WPT system diagram.

The introduction of additional intermediate resonators in the WPT system is a common way to improve the transmission efficiency and distance, negative permeability metamaterials (NPM) can improve the characteristics of evanescent wave coupling and make them one of the ideal resonators.

NPM usually has extraordinary physical properties that are not found in ordinary materials. According to Maxwell's electromagnetic field theory, negative permeability has certain advantages in reducing the attenuation of electromagnetic field. Inserting NPM into the WPT system can refocus the magnetic field and improve transmission efficiency. Generally, the preparation of NPM cells relies on PCB (Printed Circuit Board) technology, which can print metal in a certain shape on the substrate. Interestingly, NPM elements with different shapes of metal spirals will have different effects, such as quadrangle and circle. In addition, there are also different linear designs and three-dimensional metamaterials. This paper summarizes NPM cells with different shapes.

2 Effect of NPM units with different shapes on transmission efficiency of the electromagnetic resonance type WPT system

2.1 Quadrilateral NPM units

To improve the transmission efficiency of the WPT system and reduce EMF leakage, Lu et al. [14] proposed two thin plates based on electromagnetic theory and EMF theory in WPT system, namely, near-field mu-near-zero (NF-MNZ) and mu-negative permeability (MNG) metamaterials at 13.56 MHz. Negative permeability metamaterial has been demonstrated to improve the efficiency of the WPT system, and it can be theoretically deduced that the NF-MNZ metamaterial has a certain shielding ability to electromagnetic fields through Fresnel transmission and principle, laying the foundation for the reduction of EMF leakage. Using FR-4 as the base plate, a quadrilateral spiral pattern is printed on the top of the base plate with copper as the material through thin printed circuit board technology, and a capacitor is added between the two ends of the metal strip to form a single unit. Use this unit to compose 3×3 arrays, and the capacitor in the cell reduces the overall size of it. Four schemes of single NF-MNZ, single MNG, combination of NF-NMZ and NMG into the WPT system and the WPT system without metamaterial are designed for comparison. Through comparative experiments, it can be concluded that the transmission efficiency decreases when NF-MNZ metamaterial plates are placed on both sides of Tx and Rx coils of WPT system, which may be due to the effect of the metamaterial on the coupling of coils. When the NMG metamaterial plate is placed between Tx and Rx coils in the WPT system, the transmission efficiency increases to varying degrees depending on the distance between the two coils. The combination of the above two metamaterials improve the transmission efficiency of the WPT system when the distance between the two coils is 35 cm, especially when the transmission efficiency reaches a maximum at 40 cm (from 36.24% to 48.30%). Due to the existence of NF-NMZ metamaterials, the EMF leakage around the two coils is also restrained to some extent (52.84 to 20.03 μG near Tx, and 22.5 to 16.71 μG near Rx). The experimental data confirm that the designed combination of NF-NMZ and

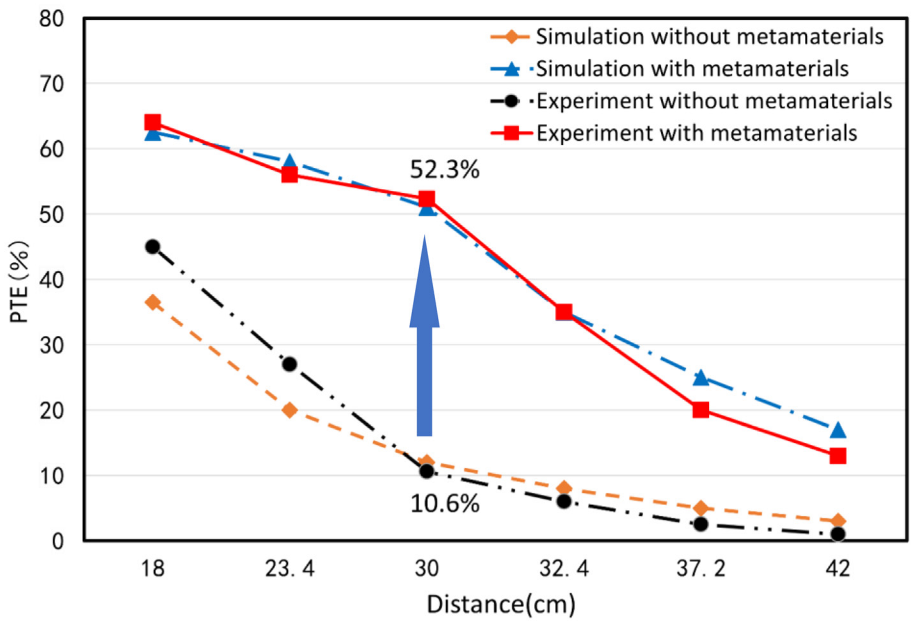

Fig. 2. Simulation and experimental transmission efficiency of original system and metamaterial system with negative permeability [15].

NMG metamaterials has certain application value in improving the efficiency of WPT systems and reducing EMF leakage.

Chen et al. [15] designed a negative permeability metamaterial with a constituent quadrilateral unit, which can improve the transmission efficiency by up to 41.7%. From the perspective of enhancing near-field coupling and weakening magnetic field divergence, the characteristics of negative permeability metamaterials can improve the efficiency of the low coupling area and reduce the impact of low efficiency on system transmission, thereby concentrating the magnetic field and enhance evanescent wave coupling. Based on this, the magnetic resonance mode WPT system has higher transmission efficiency and relatively longer transmission distance. In the EM simulation, after introducing the negative permeability metamaterial array of 2 into the WPT system, 2×2 arrays the magnetic field intensity around Tx and Rx coils increases significantly, which may be due to the coupling of the surface wave brought by the metamaterial plate and the evanescent wave attenuation of the coil, enhancing the evanescent wave amplitude. To verify the simulation, WPT systems with and without negative permeability metamaterials were designed and the transmission efficiency of the system was measured at a transmission distance of 10–60 cm, as shown in Figure 2. The results show that the placement of the negative permeability metamaterials between Tx and Rx coils can significantly improve the transmission efficiency of the system, with the best improvement (from 10.60 to 52.30%) at 30 cm. they also experimented with placing the negative permeability metamaterial plate near the coil. Although the efficiency is improved, the frequency splitting is affected by its strong coupling with the coil instead inhibits the lifting effect, which also proves that placing the negative permeability metamaterial plate in the middle of the system is the best choice. Since the NPM unit is smaller than the wavelength, the volume effect does not change much during assembly, which has a higher degree of freedom of combinations.

Based on the enhancement of magnetic coupling and amplification of evanescent waves, Guan [16] and others introduced additional resonant coils while using negative permeability metamaterial plates, which correspondingly improved the transmission efficiency of WPT systems at 27.1–27.6 MHz operating frequencies. The NPM unit is based on FR-4, and the copper wire spiral shape is quadrilateral. In order to prevent over coupling, only one side is etched. Experiments under three conditions were designed to compare the effect of resonant coil and negative permeability metamaterial on the efficiency of WPT system. Firstly, the transmission efficiency of the magnetic resonance mode WPT system without any additional factor is only 33.80% at the resonant frequencies corresponding to Tx and Rx coils, while the efficiency of the system is increased by 22.59% when the resonant coil is placed between Tx and Rx. The transmission efficiency of the WPT system can be increased to 87.98% at 27.3 MHz by placing a negative permeability metamaterial plate between Tx, Rx and the resonant coil. In addition, as shown in Figure 3, due to the frequency splitting caused by over coupling caused by the close distance between the resonant coil and the initial two coils, two efficiency peaks appear when the single resonant coil is introduced, but the bandwidth of the negative permeability metamaterial is narrow, so only in the resonant frequency range of the NPM unit, namely 27.1–27.6 MHz, has a relatively obvious efficiency improvement effect. This work attempts to combine the resonant coil and the negative permeability metamaterial plate, and the flexibility of the resonant coil in use is a major advantage, so the experimental results provide a certain reference for the practical application of this combination.

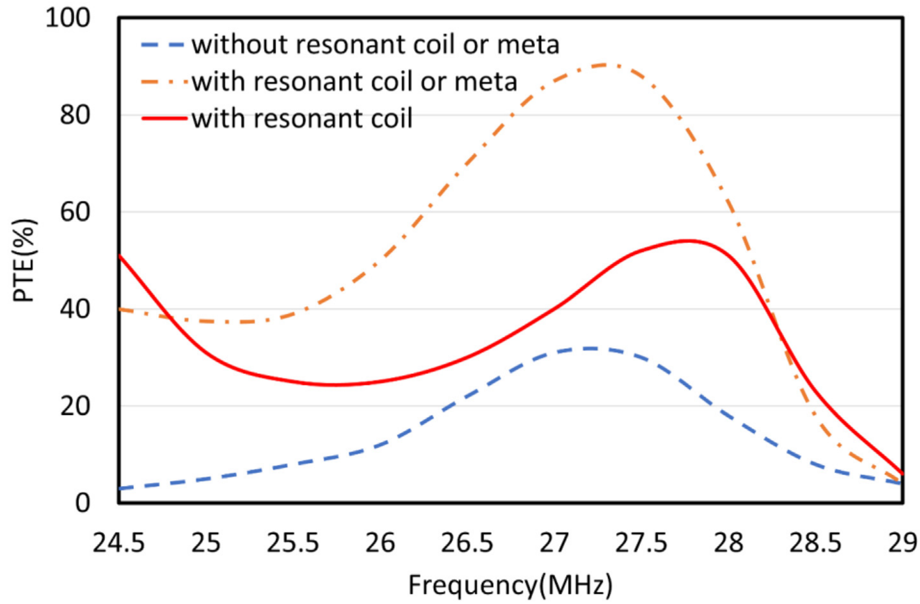

Fig. 3. Efficiency comparison of three WPT systems.

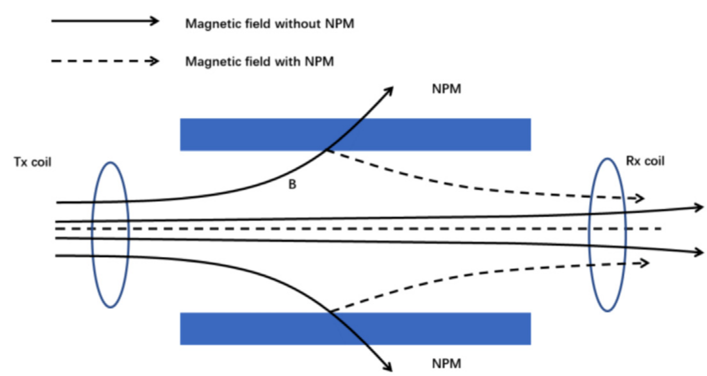

Fig. 4. Schematic diagram of ZPM Board Reducing EMF leakage.

In the above experiments, most of the extra metamaterial plates were placed in the middle of the system, while Lu [17] and others made a new attempt in the position, placing the plates on both sides of the two coil transmission channels. The results show that the efficiency is still significantly improved, which also supports for its practical application. Tn WPT system, aluminum plates are generally used to control EMF leakage. This paper proposes that zero permeability material (ZPM) has advantage over aluminum plate in this function. Due to the principle of propagating magnetic induction waves on the surface, the side-mounted NPM plate can concentrate the magnetic field between Tx and Rx coils to improve efficiency In addition, the side-mounted ZPM plate can isolate the magnetic field between the air and the plate to reduce EMF leakage. The combination of these two materials can improve efficiency and ensure safety, as measured by simulation and experiments. The combination of ZPM-NPM, compared to single ZPM and single NPM, helps to reduce the effect of the efficiency decline due to the increase of the distance between two boards, as shown in Figure 4. In practical application, complex environmental factors may cause the WPT system not to be as stable as in the experiments. For example, there may be a center or angle deviation between Tx and Rx, as shown in Figure 5. This reference also demonstrated some research on this. The experimental results show that the introduction of NPM, ZPM or ZPM-NPM can still improve the efficiency of the system in the presence of deviation. However, the single NPM plate outperformed the other two materials in reducing the center offset. When the angle offset is not more than 30°, the effect of NPM and ZPM-NPM in reducing the center offset is similar and better than that of single ZPM. When the angle offset is 45°, the single NPM significantly outperforms the other two materials.

2.2 Circular NPM unit

In the work of Ranaweera et al. [18], a negative permeability metamaterial based on acrylic acid was designed, and its NPM unit is a circular unit with three coils of spiral structure, as shown in Figure 6. The side

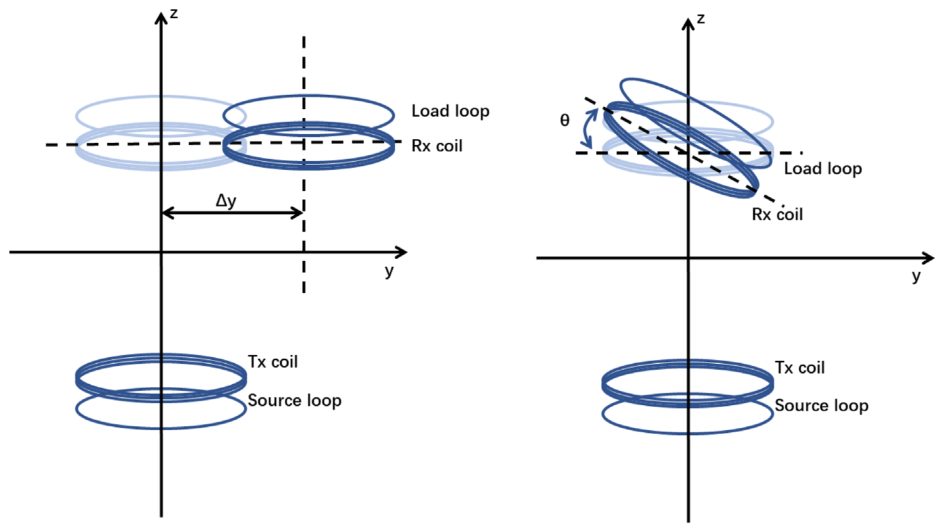

Fig. 5. Possible deviation between transmitting and receiving coils.

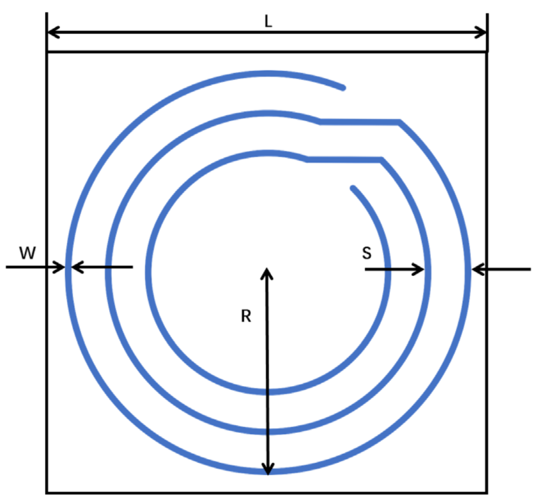

Fig. 6. Schematic diagram of NPM unit.

length of the unit L is 15 cm, in which the total diameter of the helix R is 14 cm, the line width is 7 mm, and the line spacing is 3 mm. The overall size is 1/300 of the wavelength corresponding to the working frequency (6.5 MHz) of the target WPT system, so it can be used as a high subwavelength metamaterial. In previous reports, isotropic negative permeability metamaterials can improve the efficiency of the WPT system, but large volume of isotropic materials is one of the constraints, which is contrary to the purpose of lightweight and portable WPT systems. To this end, anisotropic negative permeability metamaterials are chosen to reduce the loss of unnecessary structures. On this basis, it is also an attempt to further reduce the volume by replacing the negative definite medium with an indefinite medium. The experimental results show that the efficiency of the metamaterial plates used under the above conditions is still considerable. In addition, different coil distances, different number and spacing of metamaterial plates and different number of NPM elements are also studied in the experiment. The results show that when the Tx and Rx coils are 60 cm apart, there is no significant different in the efficiency improvement effect of single plate and double plate (7.1% and 7.7% respectively), but when the distance increases to 100 cm, the efficiency improvement effect of double plate can reach 225% of that of single plate. In terms of double plate spacing, it is also found that there is an optimal distance, which is related to Tx, Rx coil spacing and NPM unit size. The number of NPM units also affects the improvement of efficiency 5×5 arrays has the best lifting effect, and higher than this value will reduce the effect due to its own loss.

Normally, a WPT system consists of four coils, namely source coil, Tx coil, Rx coil and load coil. The metamaterial plate introduced to improve efficiency is usually placed in the middle of Tx and Rx coils, which to some extent results in the volume increase of the whole WPT system. Nguyen [19] and others tried a three coil WPT system for this purpose, using a plane receiver instead of the Rx coil, and 2×3 negative permeability metamaterial plate of the array is integrated with the receiver to reduce the volume of the entire system, as shown in Figure 7. Electronic products such as laptops cannot avoid the ground plane, and there is limited research on the impact of ground plane on the transmission efficiency of WPT system, which is also discussed in the reference. After building a simulated laptop based on the above three coil WPT system as the transmission environment, the efficiency test was conducted with or without ground cracks, and the results clearly show that the cracks can reduce the impact of ground impact on the efficiency to a certain extent. To better simulate the real charging environment, the whole system was also tested perpendicular to the ground, as shown in Figure 8. Moving the simulation computer to a different position from the center of the Tx coil, the optimal offset distance is 15 cm. The angle of the notebook receiver is also one of the factors affecting the efficiency. 90° is the optimal transmission angle, which probably because it consistent with the magnetic field coupling angle.

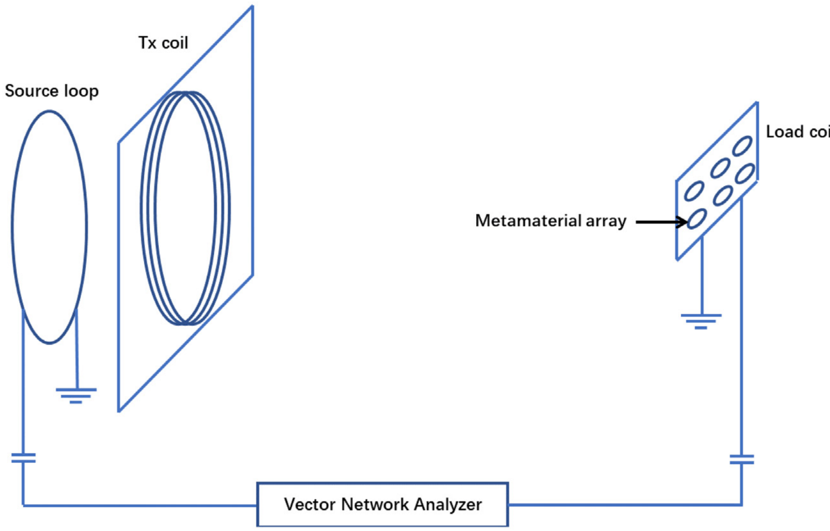

Fig. 7. Schematic diagram of three coil WPT systems.

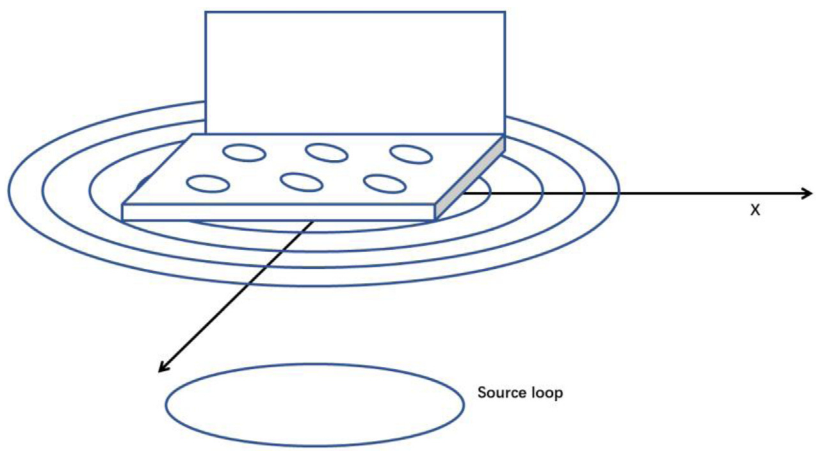

Fig. 8. WPT system position shift experiment with vertical placement.

Kim et al. [20] studied the effect of a negative permeability metamaterial plate composed of multiple circular resonant rings on the transmission efficiency of the system in a 13.56 MHz WPT system. The difference is that the metamaterial plate in this study is a three-dimensional structure with width instead of a single plate, as shown in Figure 9, where s is the width of the metamaterial plate, d is the coil spacing between Tx and Rx. The relative effective permeability μ is tested. The effect of ideal lossless plates with $\mu_r = -1$, -2 and -3 and actual lossy plates in the WPT system shows that the efficiency of the lossless plates is greatly improved due to the strong focusing effect, while due to the absorption factor of their own power, the effect of lossy plates on the system varies with the value of s/d, and is not necessarily helpful for improving the efficiency.

2.3 Other NPM units

Xin [21] and others made a different attempt on the shape of the NPM unit. They designed a hexagonal NPM unit based on FR-4 and connected the unit side by side to form a negative permeability metamaterial plate with a honeycomb structure. As shown in Figure 10, the entire unit has a radius R of 3.80 cm, an inner diameter r of 2.00 cm, and a coil spacing d of 0.20 cm. The width of the coil itself is set to 0.02 cm based on the 6.78 MHz operating frequency of the WPT system. Compared to quadrangle and circle, this design not only reduces the tip loss to a certain extent, but also concentrate the magnetic field more uniformly. In investigating the effect of metamaterial plates on the efficiency of WPT system, the experiment focused on comparing the transmission values of non-board, single board and dual board, and explored the differences between different positions of boards in the system. Simulation and experimental data show that the honeycomb structure of the metamaterial plate can improve the transmission efficiency of the WPT system and also reduce part of the EMF leakage. For the WPT system with a transmission distance of 30 cm, the efficiency of the system with double metamaterial plates inserted in the middle is 12.5% higher than that of the original system, which is the optimal condition under this design.

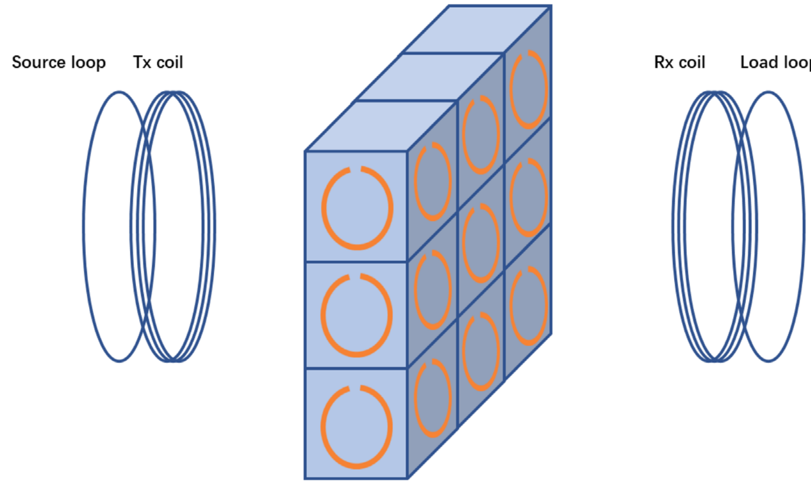

Fig. 9. Three-dimensional cuboid structure NPM.

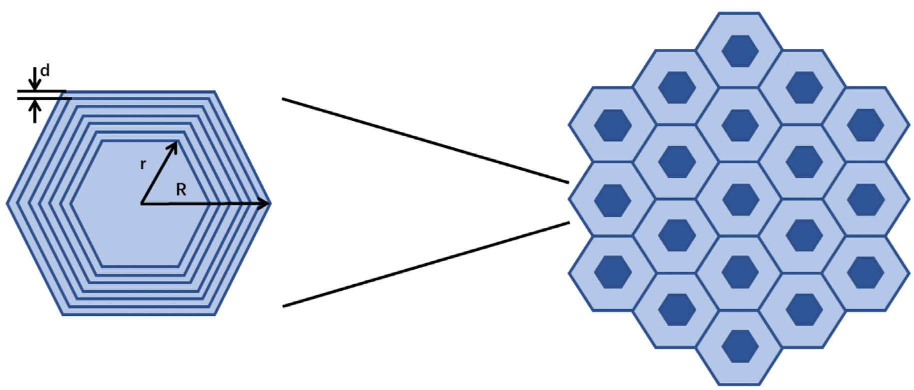

Fig. 10. Schematic diagram of hexagonal NPM.

The commonly used design structures of negative permeability metamaterial plates are mostly two-dimensional structures. The parasitic loss of such metamaterial plates prepared based on the printed circuit board technology during the printing process will reduce the quality factor, thereby weakening the effect of improving the transmission efficiency of the WPT system, and there is also a certain size limit. Erik et al. [22] made a new attempt at the shape of NPM cells. They designed a cell winding a solenoid on ferrite, as shown in Figure 11. A negative permeability metamaterial plate composed of 77 such NPM cells (the overall size is 6 cm × 6 cm × 2 cm) can produce effects at a lower operating frequency (5.57 MHz). Computational and experimental data prove that this three-dimensional structure of the metamaterial plate can improve the efficiency of the WPT system. The system with a coil spacing of 4.5 cm can increase the efficiency by 10%, and on this basis, the distance can be extended to 8.8 cm. The mutual impedance between the transmitting and receiving coils will attenuate as the working distance increases, which is one of the reasons why the efficiency of the WPT system decreases s the distance increases. However, the introduction of metamaterial plates will slow down the attenuation of mutual impedance and improve the efficiency at the corresponding distance. The lateral size of the NPM unit designed in this reference is only 1/10766 of the working wavelength. This very compact structure can reduce the volume of the WPT system to be used in small volume scenes such as biomedical applications.

Fan et al. [23] proposed the method of negative refractive index metamaterial (NRI) and negative permeability metamaterial (MNG) to improve the transmission efficiency of the WPT system in the RF band. The NPM unit in this design uses an etched double-layer design, as shown in Figure 12. One side is a central circular plate connected to a quadrilateral helix, and the other side is a serpentine line connected to two half sides. Whether it is connected to the plate side or not, determines whether it has negative index or only negative permeability. Different from the above NPM, the elements in this article can be used as NPM to achieve effects without forming arrays. The experiment result shows that NRI and MNG have the same lifting effect on the WPT system, while the negative permeability still plays a leading role. In this condition, experiments were carried out on multiple plates. The difference is that two kinds of plates are used, one of which is SSMNG (Spiral-Spiral MNG) and the other is SMMNG (Spirals-Meander lines MNG). The experiment found that the lifting effect of the double board (SM-SM) is related to the distance between the two boards and coil, and there is an optimal distance. Although the effect

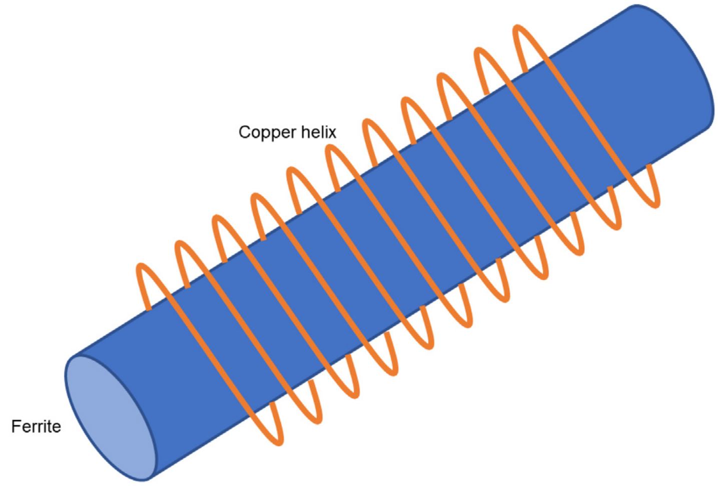

Fig. 11. Schematic diagram of ferrite NPM unit wrapped by spiral coil.

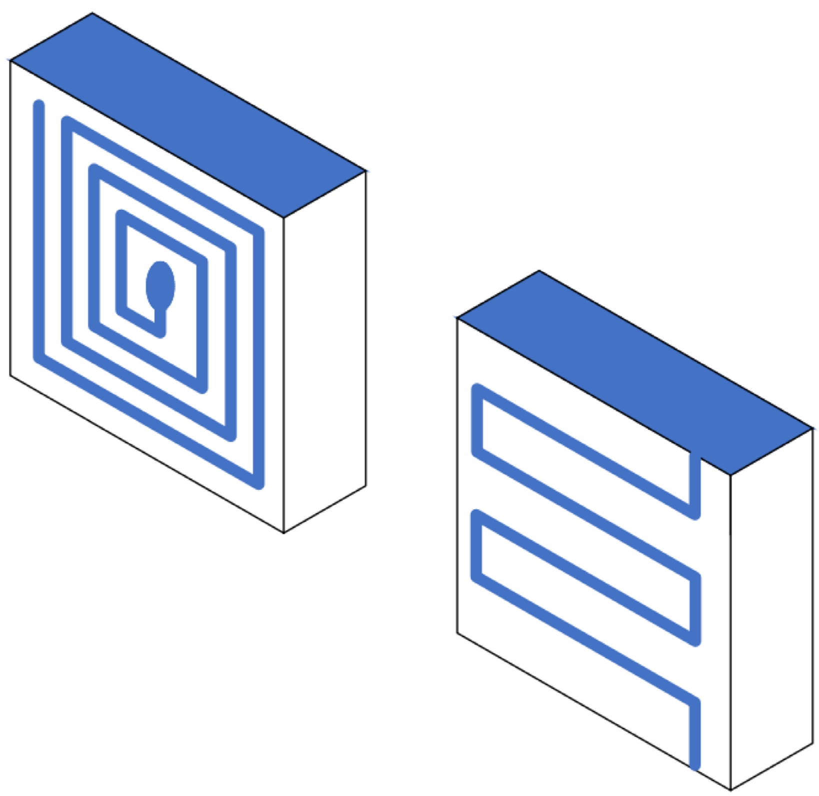

Fig. 12. Schematic diagram of negative index metamaterial (NRI).

of three boards (SM-SS-SM) and four boards (SS-SM-SM-SS) is higher than that of double boards, the strengthening effect is not obvious.

2.4 Limitations and future development

The sample sizes of NPM are large which affects the practical application of miniaturization and lightweight requirements. Large size and number of array elements lead to increased losses. How to solve this problem will be one of the focuses in the future. Exploring new materials and designing new structures is one possible approach. The working frequency of the WPT system with NPM are beyond the industry application requirement which is usually at kHz. Future work can focus on how to reduce the working frequency to kHz.

3 Conclusion and prospect

In this review, some updated research progress is comprehensively summarized from the shape of NPM elements. In conclusion, the application of NPMs with different shapes to electromagnetic resonance type WPT systems can help improve the transmission efficiency and reduce the EMF leakage. Under the premise of ensuring the same transmission efficiency, the introduction of NPMs can extend the transmission distance to a certain extent. However, the difference is that the hexagonal element is different from most attempts to improve the WPT system at the same working frequency and has also achieved some ideal results. If NPM is proposed to enhance the WPT system in actual scenarios, efficiency, compactness and light weight should be carefully considered during the design process. High efficiency can ensure the normal operation of the WPT system, compactness is the condition for WPT system to enter scenes such as human body and light weight makes the WPT system portable. All the efforts made on the NPM derived from various units have enriched the connotation of advanced WPT systems.

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