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METAMATERIALS FOR IMPROVING EFFICIENCY OF MAGNETIC RESONANT WIRELESS POWER TRANSFER APPLICATIONS

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Abstract. *In this article, we investigate a compact metamaterial structure for enhancing a magnetic resonant wireless power transfer (WPT) system operated at 6.5 MHz. A thin magnetic metamaterial (MM) slab placed between the transmitter (Tx) and receiver (Rx) coil can improve WPT efficiency. The metamaterial unit cell is designed by a ten-turn spiral resonator (10T-SR) loaded with an external capacitor. The resonant frequency of MM unit cells can be easily controlled by changing the capacitor value. By using the optimization approach, we achieve a significant WPT efficiency improvement at a mid-range distance. The results showed an enhancement of the magnetic field in the WPT system when MM slab was presented. This demonstrates the ability to amplify the evanescent wave of MM slab, thereby improving the WPT efficiency. The transmission coefficients of WPT system at 60 cm increased from 0.5 to 0.76 with MM slab, which corresponds to a 46% improvement.*

Keywords: metamaterial; magnetic resonant; wireless power transfer.

Classification numbers: 41.20.Jb, 78.67.Pt, 85.70.Ay, 88.80.ht.

I. INTRODUCTION

Wireless power transfer (WPT) has been invented longer than 100 years ago by genius scientist Nicola Tesla [1]. Nowadays, with the rapid improvement in WPT, there is a great deal of various wired power connections that can be replaced with wireless power. The accelerated development of WPT technology has shown a promising future for charging everyday electronic devices without a wire. Both near-field and far-field can be used for designing WPT [2, 3]. However, to achieve high power and good performance WPT based on near-field is more popular for conventional application [4]. Near-flied WPT is classified into two groups: (i) Inductive coupling is favored in the short-range [5]; (ii) at the mid-range distance, magnetic resonant WPT via strongly coupled of non-radiative resonant resonator is more suitable [6, 7]. The mechanism of magnetic resonant WPT relies on the coupling between two high-quality factor (Q-factor) resonators [8].

One of the challenges when designing a WPT system is that the delivered power is reduced rapidly with a large distance [9–12]. Several techniques have been proposed to improve the transferred energy. The strongly coupled resonance has been utilized to extend WPT to mid-range length (~2 m) [13]. The coupling coefficients between feed coils and resonators are adjusted to maximize the power transfer efficiency [14]. The frequency tuning is utilized to optimize the transmission efficiency when WPT is performed in the over-coupled region [15]. In [16], an automatic impedance matching technique is realized to improve the power transfer efficiency. Operating ranges of WPT have been extended using an intermediate coil [17] or using an array of resonators [18].

Metamaterials are artificially engineered materials that possess exotic electromagnetic properties, such as negative permittivity, permeability and evanescent wave amplification [19]. Metamaterials can control acoustic, electromagnetic, mechanical waves to achieve the useful characteristic [20–23]. Magnetic metamaterial (MM) is a branch of metamaterials operating at the megahertz frequency range. That contributes to several critical industrial and academic applications [24–26]. MM work on the megahertz frequency range is applicable for mid-range WPT [27, 28]. From these interests, MMs are used to improve the efficiency of the WPT system. The previous works with homogeneous metamaterial are valuable in enhancing the symmetric WPT system [29,30]. However, WPT systems and metamaterials in these works are handmade ones and have a large size.

In this article, we investigate a new metamaterial structure for improving the performance of the magnetic resonant WPT system. A compressed MM unit cell operating at low megahertz frequencies is analyzed by simulation software and fabricated by printed circuit board (PCB) technology. The real permeability of the metamaterial has been achieved from scattering parameter (S-parameter) results showing the large negative, which is useful for enhancing the evanescent wave in the WPT system. The metamaterial slab is constructed by 3×3 unit cells placed between the transmitter and receiver coil. The field distribution in the whole WPT system, including the metamaterial slab, is also considered for explaining the mechanism operation of metamaterial in WPT. At a distance of 60 cm, we obtain a transmission enhancement of 46% in the WPT system added a metamaterial slab compared with the conventional method.

II. METAMATERIAL DESIGN

Several approaches have been used to realize metamaterial. Among them, a combination of the spiral resonator (SR) with the tunable lumped-element was considered a powerful approach to apply metamaterial for WPT. In the low-frequency range, the natural resonance frequency of small SR is much higher than the desired frequency of the WPT system. Therefore, a lumped capacitor is added to reduce the resonance frequency of SR. On the other hand, The low resonance frequency reduces the Q-factor of the SR and increases the loss [30]. Thus, design a metamaterial structure for high transmission efficiency is a challenge.

Figure 1(a) describes the compact and electrically MM unit cell. It consists of ten turns spiral resonator (10T-SR) mounted with a small chip capacitor. This 10T-SR has a planar configuration so facilitate to fabricate and integrated into electrical and electronic systems. The MM

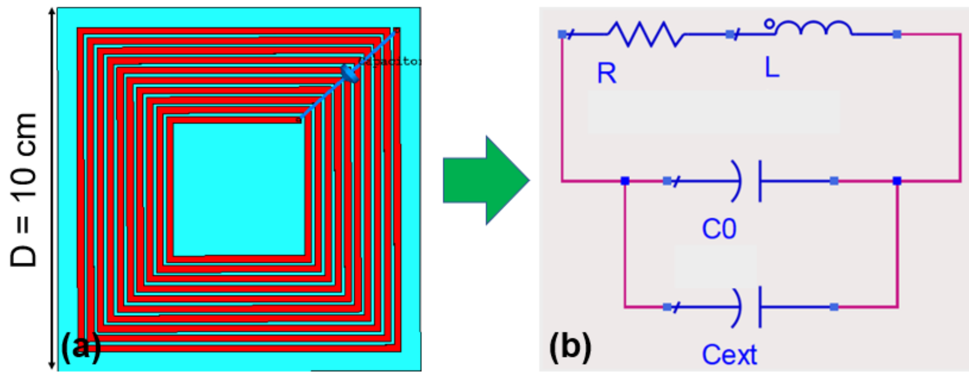

Fig. 1. (a) Sketch of a 10T-SR unit cell and (b) its equivalent circuit.

unit cell has a square shape with an outer length of 100 mm, an inter-strip space of 1 mm, and a strip width of 3 mm. The thickness of the FR-4 substrate is 1.6 mm and the dielectric constant is 4.3. The thickness of copper is 0.105 mm. An equivalent electrical model of 10T-SR is shown in Fig. 1(b). The self-inductance and self-capacitance of 10T-SR can be extracted from *S*-parameters. Here, self-inductance is $L = 9.05\ \mu$H, self-capacitance of is $C_0 = 5.05$ pF, C_{ext} is the capacitance of the added capacitor. A suitable capacitance of the added capacitor can be chosen to adjust the unit cell's resonance frequency. The ohmic losses can be taken into account by a series resistance R.

The resonance frequency of the metamaterial unit cell will be expressed as:

$$f = \frac{1}{2\pi\sqrt{L(C_0 + C_{ext})}}. \tag{1}$$

The characteristics of a metamaterial unit cell were investigated by simulation. The simulation was performed by *CST Studio Suite - 3D EM Simulation and Analysis* software. To simulate the metamaterial unit cell, we excite a lumped port to split ring antenna that has a diameter of 8 cm, which is a little smaller than the size of 10T-SR. Fig. 2 shows the resonance frequency of 10T-SR with and without a mounted capacitor. The value of mounted capacitor is 68 pF; it is a chip capacitor with a small size of $1 \times 1 \times 2$ mm. The original 10T-SR operates at 23.8 MHz, is described by black dash line. After adding capacitor, the resonance frequency of the metamaterial unit cell reduces to 6.5 MHz, which shows in the blue line. At the resonance frequency, we can see a dip in the magnitude of S_{11} appears. Thanks to the reduction of resonant frequency, the proposed metamaterial is suitable for a magnetic resonant WPT system.

In WPT system, the metamaterial can be considered as an arrangement of *RLC* resonators. Therefore, its properties are determined by the circuit parameters R, L, C, resonant frequency (ω) and filling factor (F).

Then the effective permeability of a magnetic metamaterial can be express as:

$$\mu_r = 1 - F\left(1 - \frac{1}{\omega^2 LC} - \frac{R}{j\omega L}\right)^{-1}. \tag{2}$$

The permeability of the design 10T-SR has also been achieved using EM simulation. By using CST software with appropriate boundary conditions applying for the space containing the

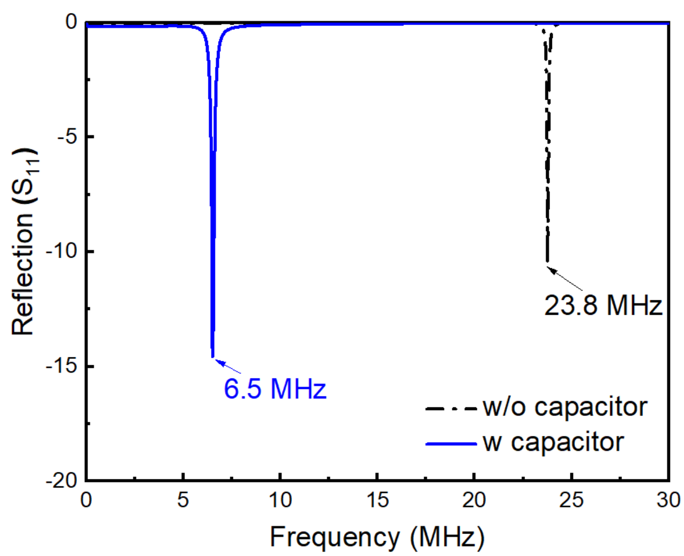

Fig. 2. The resonance frequency of 10T-SR changes with mounted capacitors.

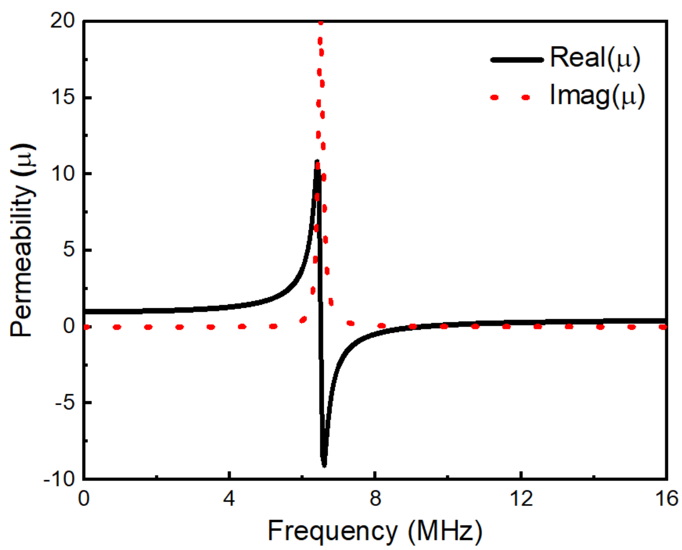

Fig. 3. Permeability of 10T-SR as a function of frequency.

MM unit cell. The real part and imaginary part of permeability can be achieved from *S*-parameter by the standard retrieval method [30]. The periodicity of the metamaterial unit cells is 100 mm when calculated the effective permeability. Fig. 3 shows the retrieved permeability of the proposed metamaterial unit cell. We emphasize that the real part of permeability is negative around 6.5 MHz. We achieved the most significant negative permeability value of -9 at 6.56 MHz.

III. METAMATERIAL FOR WIRELESS POWER TRANSFER

Figure 4 depicts the model of the proposed WPT system enhanced efficiency with a metamaterial slab placed between the transmitter and receiver coil. In this system, the metamaterial slab consists of 3×3 unit cells. The metamaterial has a planar structure with a size length is 300×300 mm. The transmitter part contains a square loop antenna with a side length of 200 mm, and a resonator coil has an outer side length of 300 mm. According to The Alliance for Wireless Power (A4WP), there is a standard frequency band for magnetic resonant wireless power transfer around 6.78 MHz. We proposed a WPT system operating at 6.5 MHz. Therefore the resonant frequency of Tx and Rx resonator needs to be designed at 6.5 MHz. After the calculation process, we found that the Tx has ten turns with the above parameter that will satisfy the resonant frequency condition. Due to the symmetry, the receiver part has the same size as the transmitter part. The separating gap of Tx resonator to the metamaterial slab is $d_{\mathrm{Tx-MM}} = 300$ mm. The space between metamaterial slab to Rx resonator is $d_{\mathrm{Rx-MM}} = 300$ mm.

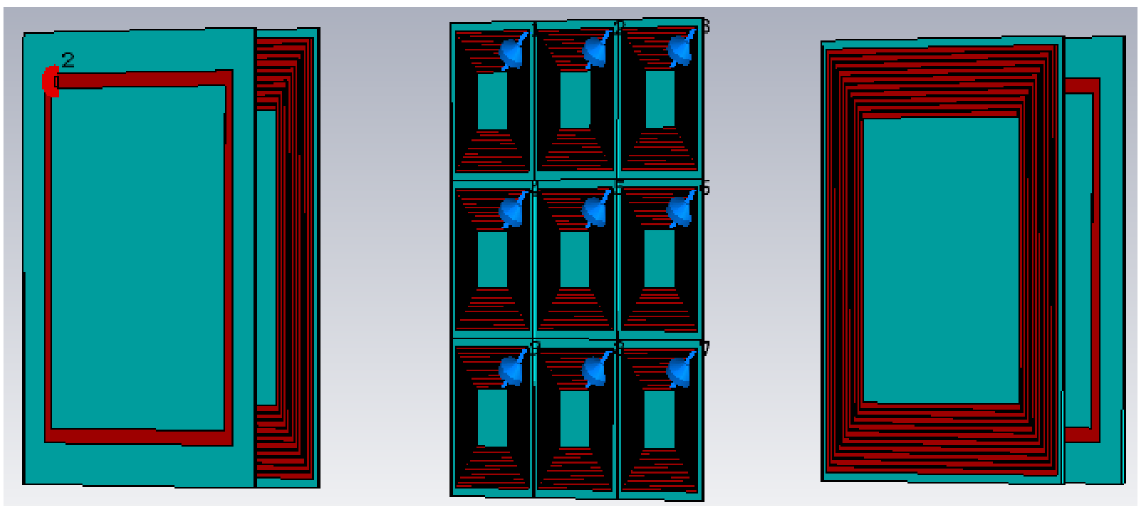

Fig. 4. Magnetic resonant WPT system with a metamaterial slab.

Figure 5(a) shows the H-field distribution around the magnetic resonant WPT system. H-field strong at the region near the Tx coil and Rx coil. However, the field at the Rx coil side is degraded, in comparison with the Tx coil side. The reduction of H-field limits the efficiency of WPT system. When a metamaterial slab is placed between Tx and Rx, the strong magnetic field representing surface waves appear on both sides of the metasurface plane, as shown in Fig. 5(b). That surface waves demonstrate the enhanced magnetic coupling and small radiated waves exist in space [26]. The H-field at the Rx side presents in red color, which means that the field is stronger in this case. The mechanism of the WPT is based on the near-field coupling between Tx and Rx through evanescent waves. That waves are dramatically degraded as the distance from the source in the positive medium. However, in the negative medium such as surrounding metamaterial slab, the evanescent wave is amplified. The above observations demonstrate that the metamaterial slab can enhance the evanescent wave in the medium between the Tx and Rx, hence improving the WPT efficiency.

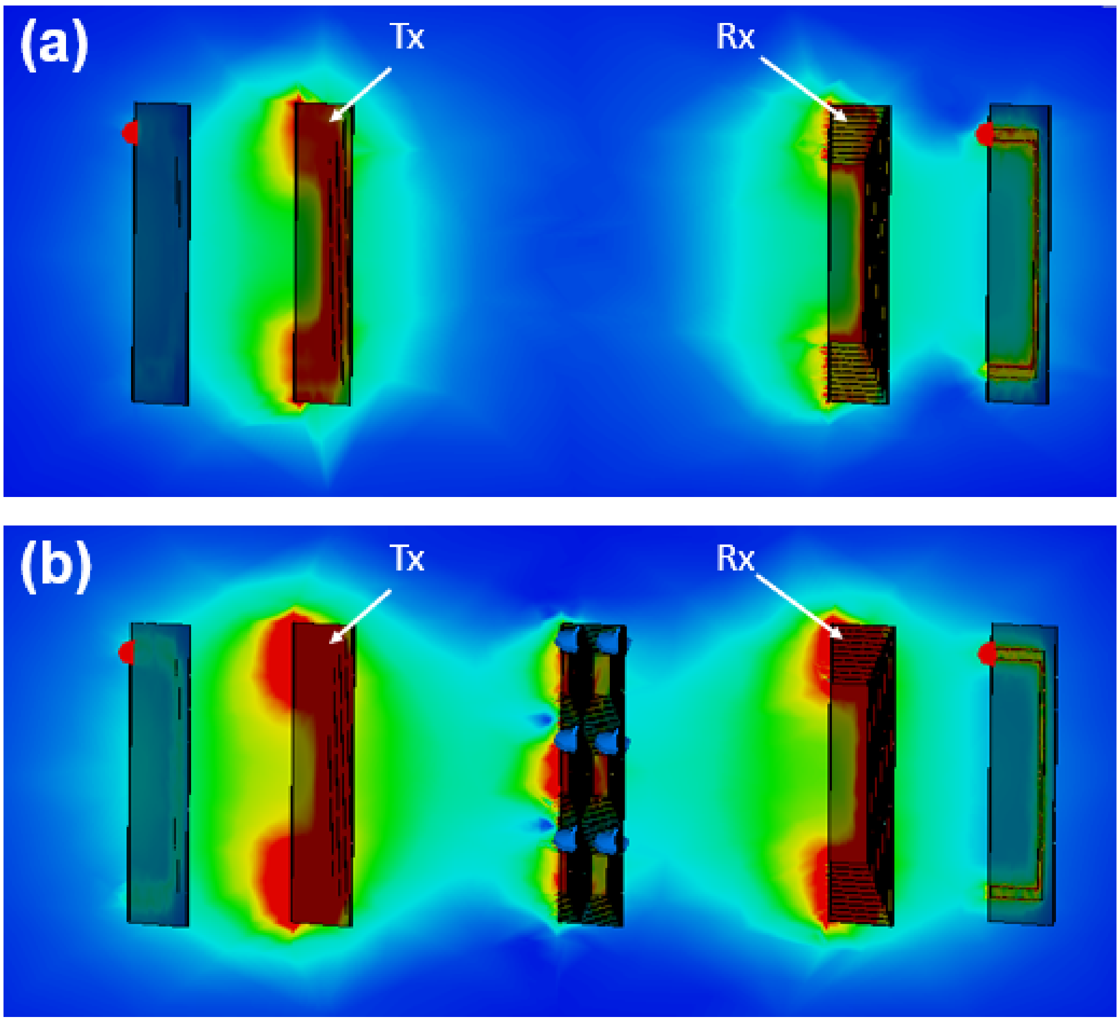

Fig. 5. Magnetic field distribution in WPT system without and with the metamaterial slab.

The effect of distance on the efficiency of WPT system has been investigated by simulation. We survey the transmission response of WPT systems at various lengths of 30, 40, 50 and 60 cm. Fig. 6 presents the transmission coefficient of WPT system as a function of frequency in black-square, red-circle, blue-triangle, and cyan-star curve, respectively. The transmission decline from 0.8 to 0.5 when the distance increase from 30 cm to 60 cm. The distance between Tx and Rx growth, which reduces the coupling coefficient of Tx and Rx. We know that two parameters are affecting the efficiency of WPT system; Q-factor and coupling coefficiency. In this case, the

Q factor of both Tx and Rx does not change because the material and structure of Tx and Rx are fixed, then the decrease of coupling coefficient can be explained for the decline of the transmission coefficient.

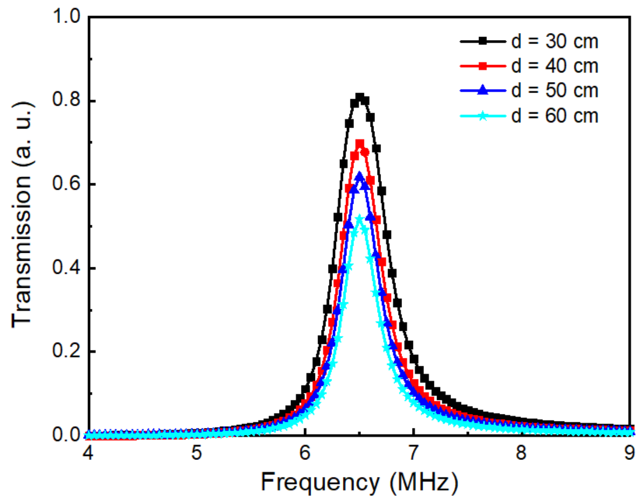

Fig. 6. The transmission coefficient of WPT system following distance.

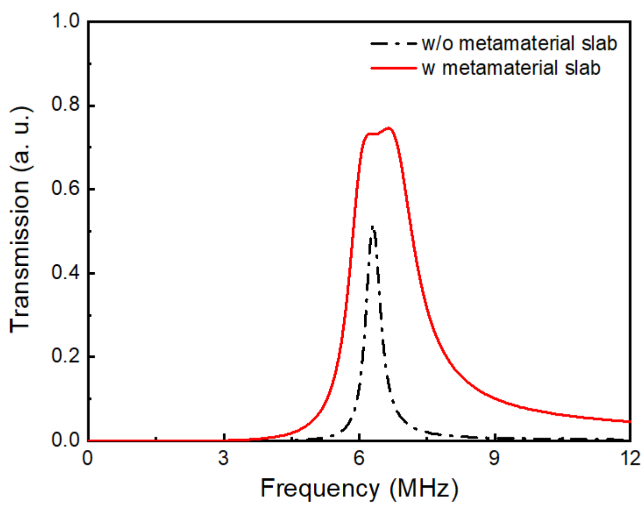

Fig. 7. Transmission response of WPT system with and without metamaterial slab.

Figure 7 compares the efficiencies of WPT system with and without metamaterials slab at the distance between Tx and Rx of 60 cm. Consistent with the field exhibition in Fig. 5, the transmission coefficient of the original WPT system is 0.5, which is shown in the black-dash line. While a metamaterial slab exists, the transmission coefficient improves to 0.73, which is shown in the red line. The transmission peak is broader with the metamaterial slab because of the inter-coupling between metamaterial unit cells in the slab. Then the total coupling of cells at the edge is less than cells at the center region. Both field distribution and transmission response have been demonstrated for the improvement of WPT system with a metamaterial slab. Using a passive device put in between Tx and Rx can enhance system efficiency. The metamaterial can be used for extending both the efficiency and transmission range of WPT system.

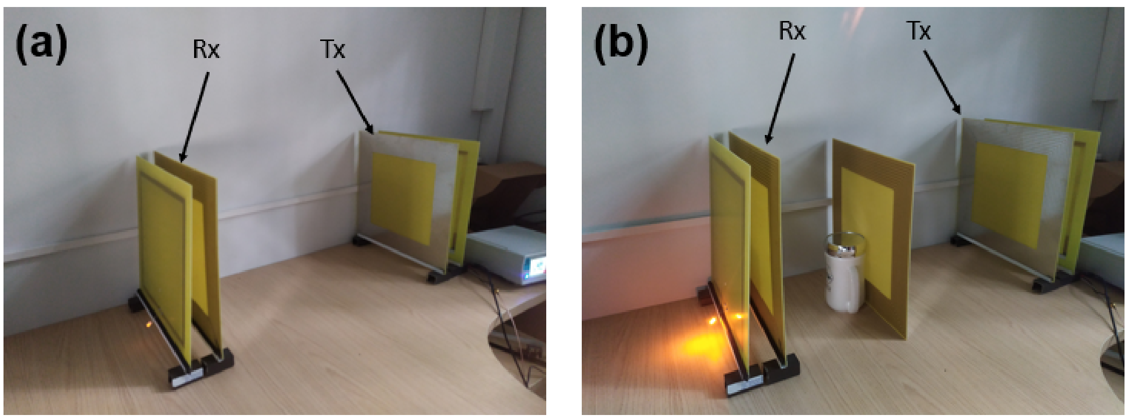

Fig. 8. Magnetic resonant WPT system (a) without metamaterial slab, (b) with metamaterial slab.

Figure 8 presents the magnetic resonant WPT system load with a lamp. The distance between Tx and Rx is 60 cm. We can see that power can transfer from Tx to the Rx of WPT system and light the lamp. But the brightness of the lamp is low because of the low transmission coefficient at the considerable distance. When the metamaterial slab is put between of Tx and Rx lamp is much brighter while the distance from Tx to Rx is kept at 60 cm. This experiment demonstrates that the power transfer of WPT system can be enhanced significantly using a metamaterial slab.

IV. CONCLUSION

In this paper, we design a compressed metamaterial for improved performance of magnetic resonant WPT system. The designed metamaterial has a planar structure of 3×3 10T-SRs. Several simulation configurations of magnetic resonant WPT systems including metamaterial slab have been processed. The EM simulations present that the strong surface wave travels along with the metamaterial slab, thus, enhance the transmission coefficient. Compared to the case without metamaterial slab, we observed the improvement of the transmission coefficient from 0.5 to 0.73, corresponding to 46%, at a distance of 600 mm. The result proves that the designed metamaterial structure effectively improves the power transfer capability of a magnetic resonant WPT system. The metamaterial slab has a thin shape and a standard fabrication method. Therefore it can reduce the cost and space required of WPT system.

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