Book Chapter

Using Artificial Magnetic Conductors to Improve the Efficiency of Wireless Power Transfer

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Abstract

In this study, an advanced wireless power transfer (WPT) system of two coils with the artificial magnetic conductors (AMC) is explored through simulations and experiments. The AMC structure is added on the transmitter coil, and the multiple resonant modes on the surface of the AMC can be energized. On the other hand, the AMC structure act as a magnetic field shield, which leads to the magnetic field above AMC structure is localized. Therefore, the localized resonant magnetic field enhance the transmission coefficient of the WPT system. The results show that the WPT transmission coefficient is increased from 16% to 35% in the experiment at 26.2 MHz resonant frequency when transmission distance is 3 cm. The experimental results agree with the simulation results. Additionally, AMC has the advantages of low-cost and can easily be installed on the WPT system.

Introduction

With continuous development of the Internet of Things (IoT) [1] and artificial intelligence, an increasing number of intelligent IoT devices are being used in homes, cities, transportation, and space, which connect to the internet with a flexible and real-time power supply. Such energy demands have rapidly expanded the

application requirements and scope of wireless power transfer (WPT) technology, which is now becoming indispensable for providing convenient, safe, and highly efficient daily transfer of electric energy. Specifically, this technology has already been used in many different fields including consumer electronics [2], biomedical implants [3], electric vehicles [4], wireless power supply tracks for electric vehicles [5], wireless sensor networks [6], and wireless charging [7].

In the early 20th century, Nikola Tesla [8] proposed the concept of WPT. Later, in 1963, Brown et al. [9] first demonstrated WPT technology using far-field microwaves through experiments. In 2007, Kurs et al. [10] performed an experimental demonstration of magnetic-couple resonant WPT, which can be used for mid-range WPT applications. Since then, a variety of harmonic oscillator and transmission path design plans have been proposed to improve the transmission efficiency of WPT technology [11]. It is known that magnetic fields are powerful and safer medium for WPT. Regulating magnetic fields is a reliable way to improve all aspects of WPT performance. Metamaterials and metasurfaces with peculiar electromagnetic characteristics can strengthen and broaden the way of regulating electromagnetic fields and waves. In 2011, Wang et al. [12] introduced metamaterial in the WPT system, where an artificial material with a specific surface structure made from metamaterial is placed between the transmitter and receiver coils. This approach was found to amplify the evanescent waves during electromagnetic field transmission and therefore greatly improve the transmission efficiency of the WPT system. Subsequently, multiple microstructure materials have been used in the WPT system [13-18] for regulating the near electromagnetic field and increasing the WPT efficiency or distance.

Artificial magnetic conductors (AMC) are an artificial microstructure material with a special surface structure [19-25], which was first proposed by Sievenpiper in 1999 [21]. It is made by etching a copper clad plate and exhibits a high-impedance surface structure and very small tangential magnetic fields. When applying this material to antenna, the high impedance at the surface of the AMC can achieve simultaneous regulation of

surface wave suppression and zero phase reflection. Therefore, this technique can greatly enhance directional gain and enable miniaturization of low profile antenna [23-25]. In 2013, Wu et al. [26] proposed implementing a perfect magnetic conductor (PMC) in the WPT system as a reflector and predicted enhanced transmission efficiency through simulations. In 2015, Kamoda et al. [27] studied dual-band RF energy harvesting loop antennas over AMC with impedance matching, and the working frequency is hundreds of megahertz. In 2015, Lawson et al. [28] performed simulation analyses by applying a capacitor-embedded AMC in magnetic-induced WPT, however the dielectric material of simulation AMC is ferrite which is bad for experiment and application. Their study confirmed that the AMC structure can effectively shield electromagnetic waves. In this paper, we applied an AMC structure embedded with a chip capacitor to a WPT system and analyzed the transmission efficiency of WPT by both simulations and experiments. Our analysis reveals different efficiency improvements under different frequency conditions, which are further rationalized based on the phase distribution and near magnetic field distribution. Compared to the previously discussed research of Wu et al. and Lawson et al. [26-28], the AMC-integrated WPT system proposed in this study is realized in simulation and experiment at Tens of megahertz, and this system has a simpler layout and is easier to implement in practical applications. Specifically, our design only requires AMC structure packing in the transmitter end and can achieve a switchable working mode between two different frequencies.

Structural Design

Figure 1: (a) Schematic of the WPT structure; (b) schematic of the AMC unit cell structure; and (c) AMC experimental sample.

Figure 1(a) shows the structure of the WPT system used in this study. From top to bottom, the system is composed of a receiver coil, a transmitter coil, and the AMC. Both coils have the same diameter and the surface of the AMC is placed parallel to the coil. In this study, the wire diameter and outer diameter of the coils are 2 mm and 150 mm, respectively. The AMC material exhibits a mushroom structure [21] and consists of small patches periodically arranged on the dielectric substrate. Each patch is grounded by a via passing through its center hole. Chip capacitors are soldered in the gaps between the adjacent patches. In this study, six rows and six columns of patches are used to prepare the AMC structure. Each copper patch is a square measuring $58 \times 58 \text{ mm}^2$. The gap between adjacent patches is 1 mm. The capacitance of the chip capacitor is 4.7 nF. The vias have a diameter of 1 mm and are made by copper plating. The printed circuit board (PCB) medium is 5 mm thick and is made of F4B250 with a dielectric constant of 2.5. These components are shown in Figure 1(b) and (c). It should be emphasized that

this structure has a low requirement for the dielectric constant of the PCB material and is therefore very low cost. Because of the dielectric constant of the PCB does not influence the working frequency and efficiency of the WPT with AMC system.

The parameters are optimized by WPT with AMC system time-domain simulation, the AMC unit Eigen mode simulation and Composite right/left-handed transmission line theory [29]. The optimized parameters mainly consist of the number of units, the thickness of PCB medium, the capacitance of the chip capacitor, the dielectric constant of PCB medium, the patches size and the coil outer diameter.

Figure 1(a) also shows that the AMC and receiver coil are placed on two different sides of the transmitter coil. The advantage of such an arrangement is that it allows the transmitter coil and AMC structure to be bundled together and at the same time eliminates any obstacles between the transmitter and receiver coil. Therefore, this type of structure can be more easily achieved in an actual product.

Simulation and Experimental Results

The simulation study is performed using CST MICROWAVE STUDIO (MWS), a 3D EM simulation software based on the finite-difference time-domain (FDTD) method. The experimental results are measured using vector network analyzer Keysight E5063A. The transmitter coil and receiver coil openings are a discrete source port and a discrete load port in simulation, respectively. The transmitter coil and receiver coil openings are linked to SMA port in experimental measurement. When the source port is powered on, the transmitter coil generates magnetic fields. Part of the magnetic fields energy will be absorbed by the receiver coil due to electromagnetic induction and part of the energy will act on the AMC structure placed on the other side of the transmitter coil. There are six unit cells arranged in both horizontal and vertical directions of the AMC structure. Each unit cell is composed of the PCB medium, chip capacitor, top copper sheet, copper plated via, and a bottom copper substrate, as shown in Figure 2. According to Composite

right/left-handed transmission line theory²⁹, the equivalent parts include right-hand capacitance C_R , left-handed capacitance C_L , right-hand inductance L_R , left-handed inductance L_L and resistance R . There are two prominent resonant frequencies $\omega_1 = 1/\sqrt{C_R L_L}$ and $\omega_2 = 1/\sqrt{C_L L_R}$ to the simulation results of WPT with AMC system in this paper, and the AMC unit Eigen mode solution show that the working frequency is greatly influenced by the capacitance of chip capacitor, the gap distance between neighbouring patches and the thickness of PCB medium. As the capacitance of the chip capacitor is much larger than the equivalent capacitance of the gap, each chip capacitor provides an equivalent capacitance of C and each copper via connecting the chip with the ground provides an equivalent inductance of L . In this way, an LC equivalent circuit is formed in each unit cell. In other words, each unit cell now acts as a single harmonic oscillator. Due to the periodic configuration in the AMC structure, these harmonic oscillators can couple with each other and enable multiple coupling modes. When excited by the near magnetic field, part of the coupling modes are activated, which induces the resonance phenomenon.

Figure 2: Equivalent circuit model of the AMC structure.

More magnetic field energy can be transmitted at the resonance frequency, as shown in Figure 3. Figures 3 (a) and (b) show a comparison of the transmission coefficient ($|S_{21}|$) of both the transmitter and receiver coil with and without the AMC structure obtained from simulations and experiments. The solid line

corresponds to the AMC structure and the dashed line corresponds to no AMC structure. The distance is 30mm between the transmitter coil and the receiver coil, in Figure 3. As shown in Figure 3(a), a maximum $|S_{21}|$ of 55% was reached at a resonance frequency of 29.10 MHz. This value demonstrates a 35% improvement over that obtained without the AMC structure. The experimental measurement also revealed a maximum $|S_{21}|$ of 35% with the AMC structure, as shown in Figure 3(b). Due to the energy loss and measurement error, the resonance frequency obtained from experiments can be slightly different from that obtained from the simulation. Soldered chip capacitors lead to series resistance loss. This loss exist in every gap between the adjacent patches, it weaken the mutual coupling between the resonant units. So the performance of coupling modes is affected in experiment. Figures 3(c) and (d) show the change in $|S_{21}|$ as a function of distance for both the transmitter and receiver coil with and without the AMC structure obtained from the simulation and experiments. The solid line shows the results for coils with the AMC structure and the dashed line corresponding to without the AMC structure.

Figure 3: (a) and (c) $|S_{21}|$ plot and change in $|S_{21}|$ as a function of distance from the coil obtained from the simulation; (b) and (d) $|S_{21}|$ plot and change in $|S_{21}|$ as a function of distance from the coil obtained from the experiments;

It can be seen from Figure 3 that including the AMC structure yields an improvement of approximately 35% in the overall $|S_{21}|$. At 10 mm distance from the transmitter and receiver coil, the enhancement reaches 70%. In addition, multiple peaks are observed in Figure 3(a) and (b), which shows that excitation from the near magnetic field induces multiple resonance modes in the AMC structure. Therefore, introducing the AMC structure in a WPT system can enable power transmission over multiple frequencies. Meanwhile, the resonance frequency associated with the AMC structure can be tuned by changing the structural parameters, including the capacitance of the chip capacitor, the gap distance between neighbouring patches, and the height of the copper plated via. Among all parameters, the capacitance of the chip capacitor has the greatest impact on the resonance frequency, while the other parameters can be fine-tuned.

Figure 4: (a), (b), (c), (d), (e) Side distribution of the magnetic field associated with the five resonance frequencies shown in Figure 5; (f) is the side distribution of the magnetic field in the absence of an AMC structure.

The AMC structure in the WPT system in this paper that have five resonant modes. The reason may be the multiple units of AMC and coupling effect between them. And the larger the number of the AMC units can produce more modes.

In order to better explain the physical mechanisms behind the enhanced efficiency, the side distributions of the magnetic fields are shown in Figure 4 (a) - (e) with respect to the five resonant frequencies in Figure 5. Figure 4 (f) illustrates the side distribution of the magnetic field in the absence of an AMC structure. These figures reveal that, without the AMC structure, a significant portion of energy is dissipated from the other side of

the transmitter coil, opposite to the receiver coil, in a resonance-free double coil WPT system. Only a limited amount of energy is absorbed by the receiver coil. However, after introducing the AMC structure, the magnetic field is shielded and retained above the AMC structure as shown in Figures 4 (a) - (e). The shielding effect leads to the magnetic field above AMC structure is localized. It is also one reason that the power transmission efficiency is enhanced. This finding proves that the AMC structure can effectively localize magnetic fields with a frequency at the MHz level. Most conventional magnetic materials are limited to a working frequency of less than 1 MHz, and existing materials for shielding MHz magnetic fields are very expensive.

Figure 5 shows the reflective curve obtained at the entrance of the electromagnetic wave in the transmitter coil with (solid line) and without (dashed line) the AMC structure. A local minimum value is reached at certain frequencies on the reflective curve, which indicates that the magnetic field energies associated with these frequencies are strengthened by using the AMC structure. It is known these frequencies are resonance frequencies. This finding explains our previous results from another perspective: the efficiency of the WPT system is improved at resonance frequencies when using the AMC structure. Furthermore, the magnitude of the five minimum values at the resonance frequencies (Figure 5) do not agree with the magnitude of the efficiency at these resonance frequencies, shown in Figure 3(a).

Figure 5: Reflection at the port of the transmitter coil

Figure 6: (a), (b), (c), (d), (e) Magnetic field phase diagram measured at the same height as the receiver coil and associated with the five resonance frequencies shown in Figure 3(a); (f) is the magnetic field phase diagram measured at the same height as the receiver coil in the absence of an AMC structure.

Figure 7: (a), (b), (c), (d), (e) Magnetic flux distribution map measured at the same height as the receiver coil and associated with the five resonance frequencies shown in Figure 3(a); (f) is the magnetic flux distribution map measured at the same height as the receiver coil in the absence of an AMC structure.

To explain this problem, the magnetic field phase diagram and magnetic flux distribution map measured at the same height as the receiver coil are shown in Figures 6 and 7. Figures 6 (a) - (e) show the magnetic field phase diagram obtained at the same height as the receiver coil, where each is associated with one of the five resonance frequencies shown in Figure 3(a). Figures 7 (a) - (e) show the magnetic flux distribution map associated with the five resonance frequencies shown in Figure 3(a). These magnetic flux distribution maps are also obtained at the same height as the receiver coil. The phase diagrams reveal different transmission modes associated with the magnetic field distribution at the five different resonance frequencies. Figures 6 (a) and (b) correspond to two different first order modes, figures 6 (c) and (d) correspond to two different second order modes, and Figure 6 (e) corresponds to one type of third order mode. As the transmission mode changes from one frequency to another, the number of nodes associated with each mode increases in the receiver coil and the direction of the magnetic flux also changes significantly. Consequently, some of the magnetic fluxes cancel each other out due to the opposite projection direction (figure 7 (a) - (e)). For comparison, Figures 6(f) and 7(f) show the magnetic field phase diagram and magnetic flux distribution map

at the receiver coil in the absence of an AMC structure. For example, magnetic fluxes are only perpendicular to the receiver coil in the center of the coil, and others fluxes are incline or parallel to the coil far from the center, in the figure 7(c). Therefore, the magnetic fluxes is much smaller in the figure 7(c) than the figure 7(a) that the magnetic flux are all perpendicular to the receiver coil in the interior of the coil. Simultaneously, the magnetic field intensity in the figure 7(c) is also far less than the figure 7(a). So, the transmission efficiency in the figure 7(c) is not comparable to the figure 7(a). Next, compare to the Figure 7(c) and (f), the magnetic fluxes is perpendicular to the receiver coil in the larger part of coil middle as shown in the figure 7(f), and others fluxes incline to the coil in the edge of the coil. Though the magnetic field intensity in the figure 7(c) is slightly larger than the figure 7(f), the transmission efficiency in the figure 7(c) is comprehensively smaller than the figure 7(f). Similarly, the transmission efficiency in the figure 7(d) and (e) is also lower than the figure 7(f).

In addition, Figures 8 and 9 show the planar magnetic field maps in the AMC structure associated with the five resonance frequencies shown in Figure 3(a). In figure 8 and 9, the position of planar magnetic field maps is same as the position of the AMC surface. For figure 9, the Measuring probe is RF semi-steel wire whose core wire ending is shaped as 0.6mm diameter loop. As illustrated in the figures, different local modes of the magnetic field are obtained at different resonance frequencies. This scenario can be used to enable a dual-frequency working mode in the WPT system. Moreover, if a certain working frequency is affected or conflicted during operation, one can switch to a different working frequency at any time. This feature significantly increases the convenience of practical applications.

Figure 8: (a), (b), (c), (d), (e) Simulation results of the local magnetic field in the AMC structure surface associated with the five resonance frequencies shown in Figure 3(a).

Figure 9: (a), (b), (c), (d), (e) Experimental results of the local magnetic field in the AMC structure surface associated with the five resonance frequencies shown in Figure 3(a).

Conclusion

This study analysed the effect of an artificial magnetic conductor (AMC) structure for improving the efficiency of the wireless power transfer system using both simulation and experimental methods. The results showed that introducing the AMC structure can shield the magnetic field and enable more efficient dual-mode working conditions due to the effect of the resonance units. The resonance frequencies of the AMC structure can be tuned by adjusting the capacitance of the chip capacitor. The range of the working frequency can also be set according to the actual requirements. Furthermore, because the AMC structure is placed at the other side of the transmitter coil, opposite to the receiver coil, the configuration is more easily implemented in practical applications compared to installing an additional structure between the transmitter and receiver coil. Therefore, for a practical wireless power transfer system, the AMC structure is a more viable option due to its low cost and simple integration.

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