High Efficiency Metamaterial-based Multi-scale Wireless Power Transfer for Smart Home Applications

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*Abstract*—This paper presents a high efficiency multi-scale wireless power transfer (MSWPT) system using a metamaterial slab consisting of 2 × 2 spiral unit cells, which operates at 6.78 MHz (AirFuel Alliance standard frequency) for near-field WPT and 433 MHz (ISM band for smart home devices) for far-field WPT. The MSWPT system is configured to have the power transfer efficiency (PTE) greatly enhanced with the MTM slab which has an electromagnetic wave focusing capability for both frequency bands. A prototype of the MSWPT system is designed, fabricated, and characterized. The PTE of the fabricated MSWPT at a distance of 50 cm is increased from 5.42 % to 50.12 % with the MTM slabs at 6.78 MHz, i.e. 9.25 times enhancement while the PTE at a distance of 1.4 m is increased from 2.3 % to 9.38 % with the MTM slabs at 433 MHz, i.e. 4.08 times enhancement. It is concluded that the transition from 6.78 MHz near-field WPT to 433 MHz far-field WPT is advantageous in the MSWPT when the distance is greater than 90 cm.

*Keywords*—Wireless power transfer (WPT), metamaterial, multi-scale WPT (MSWPT), power transfer efficiency (PTE).

1. Introduction

Recently, the high demand for wireless power charging in the modern electronic systems due to its convenience and mobility supporting nature has stimulated active research and development of wireless power transfer (WPT) technologies. In general, WPT technology is divided into two categories, namely, near-field and far-field WPT. The near-field WPT refers to a WPT with a power transfer distance (PTD) less than its working wavelengths. The most widely used technologies coming under this category are inductive coupling-based WPT and magnetic resonant coupling (MRC)-based WPT. However, although the MRC-based WPT extends the power transfer distance to a mid-range distance (cm ~ m), the increase of the PTD reduces the magnetic coupling between the transmitter (Tx) and receiver (Rx) coils so that the power transfer efficiency (PTE) of the WPT degrades, and the PTD of the MRC-based WPT is limited [1]. As for the far-field WPT, microwave power transfer called radiative WPT is included to this category. In the far-field WPT, radiative energy emitted from a Tx antenna propagates through the air over a far distance. This electromagnetic (EM) wave can be captured by an Rx antenna. But, as microwaves propagate in omni-directions, high path losses occur for far distance transmission, thereby making the PTE relatively low.

In recent years, researchers have reported that metamaterials (MTMs) can be utilized for improving the PTE of the near-field WPT, called MTM-based WPT [2]. MTMs are artificially engineered materials that have unusual electromagnetic properties, such as evanescent wave amplification and negative refraction, thereby enhancing the PTE [3]. The reported MTM slabs have been inserted between Tx and Rx coils to increase the PTE of the WPT system [4]-[7]. However, some MTM slabs are too large and thick to be applied to practical applications. In addition, the PTD of the previously reported MTM-based WPT systems is still limited. Meanwhile, MTMs have been also utilized for the gain enhancement of the antenna as a form of MTM superstrates [8]-[9], where MTM superstrates help improve the antenna gain, taking advantage of the near zero refraction property of the MTM. In [10], an MTM-inspired dual-function antenna for both WPT and wireless communications has been proposed. However, only a single Rx device has been implemented, not an entire system. Moreover, WPT performance for both frequencies has not been fully investigated.

In this work, we report for the first time a high efficiency MTM-based multi-scale WPT (MSWPT) system for smart home applications where the MTM incorporated coil/antenna system is designed to operate in both the near-field scale (6.78 MHz AirFuel Alliance standard frequency) and the far-field scale (433 MHz ISM band for smart home devices) for WPT. As MTM slabs are configured to have a beam-focusing property for both 6.78 MHz and 433 MHz, the PTE of the WPT system for both scales can be significantly improved.

1. Design and Analysis of the Metamaterial-based Multi-scale WPT System



Fig. 1. Concept of the metamaterial-based multi-scale wireless power transfer (MSWPT) system for smart home applications.

1. Multi-scale Operation

Fig. 1 shows the concept of the MTM-based MSWPT for smart home applications. The MSWPT system is configured to work as near-field and far-field WPT according to its PTD. When the Rx is located within the near-field scale (6.78 MHz), the MSWPT operates in the magnetic resonance coupling WPT mode. If the Rx is located outside the boundary of the near-field scale, the MSWPT is operated in the radiative WPT mode (433 MHz).



Fig. 3. Simulated and measured return losses of the Tx/Rx parts for: (a) 6.78 MHz, (b) 433 MHz.



Fig. 2. (a) Geometry of the MTM-based MSWPT system. (b) Configuration of the MTM unit cell, where *L*M = 150 mm, *D*M = 140 mm, *W*M = 7 mm, *G*M = 3 mm. (c) Configuration of the Tx/Rx part, where *D*L1 = 180 mm, *D*L2 = 180 mm, *W*L = 1 mm, *G*L = 10 mm.

The multi-scale property of the MSWPT system comes from the capacitors that are connected to the Tx, Rx, and MTM unit cells as shown in Fig. 2. When the working frequency is comparably high such as 433 MHz, the capacitive reactance of the connected capacitors, , becomes very small so that the connected capacitor can be considered to be shorted. It means that in the high frequency range, the resonant frequencies of the Tx, Rx, and MTM unit cells are not affected by the connected capacitors, but only determined by their coil/antenna structures and their dimensions and geometry. Meanwhile, when it comes to the low frequency range such as 6.78 MHz, capacitive reactance, becomes unignorable due to the low value of the . The connected capacitor could be utilized to tune the resonant frequencies of the Tx, Rx, and MTM unit cells. This property of the capacitive reactance in a different frequency range is exploited for the operation of the multiple frequency based self mode-selective MSWPT. Once the dimension of the far-field coil/antenna is determined, the value of the connected capacitor is selected for the near-field resonance operation.

1. Design of the WPT System



Fig. 5. Measurement setup for the proposed MTM-based MSWPT system in an anechoic chamber.



Fig. 4. Simulation results of the MTM unit cell: (a) Effective permeability result for 6.78 MHz, (b) Effective refraction index result for 433 MHz.

The configuration of the MSWPT system integrated with 2 × 2 MTM slabs at the front sides of the Tx and Rx parts is presented in Fig. 2(a). First, the MSWPT system (Tx/Rx parts) is designed as shown in Fig 2(c). The WPT system consists of the Tx part (a source coil and a Tx coil) and the Rx part (a load coil and an Rx coil) which are fabricated on a 1 mm thick acrylic slab (. For a multi-scale property, a 220 pF capacitor is connected to Tx and Rx coils in parallel. High Frequency Structure Simulator (HFSS, Ansys Inc.) is utilized to simulate a full 3D structure of the proposed system. Fig. 3 shows the simulated and measured return losses of the Tx/Rx parts for (a) 6.78 MHz and (b) 433 MHz. It shows that the proposed WPT has a multi-scale property and the measured return loss matches well with the simulated one.

1. Design of the Metamaterial Slab

The designed MTM slab consists of 2☓2 MTM unit cells (Fig. 2(a)). In this work, a square spiral shaped resonator is utilized for the unit cell since it has a higher Q-factor than a split ring resonator one [11]. The unit cell is fabricated on a thin polyethylene substrate ( which has a thickness of 0.0762 mm. The thickness of the metal (copper) is 0.0799 mm. For a multi-scale property, a 110 pF capacitor is connected to each unit cell in parallel. The effective refractive index of the MTM can be obtained from the simulation results by using the standard retrieval methods [12]. In general, in order to calculate the , both effective permittivity and permeability are needed [3]. However, in a deep sub-wavelength limit that is the case of the 6.78 MHz WPT, the magnetic and electric field decouple, and only is required to obtain a negative . Meanwhile, in the case of the 433 MHz WPT, the device size is not much smaller than the operating wavelength, which does not fall in the deep subwavelength limit. Therefore, both and are needed to achieve of the MTM.

Table 1. Comparison of the demonstrated work with previously reported MTM based WPT Systems.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Ref. | (MHz) | | (mm) | , |  | PTE  with MTM (%) | FoM |
| [4] | 27 | | 400 | -1 | 1.25 | 47 | 0.59 |
| [5] | 7.43 | | 150 | 0, -1 | 1.33 | 18.6 | 0.25 |
| [6] | 5.57 | | 40 | -1 | 1 | 35 | 0.35 |
| [7] | 6.78 | | 600 | -1, -3 | 1.5 | 63.04 | 0.95 |
| **This work** | **Near** | **6.78** | **180** | **=-1** | **2.78** | **50.1** | **1.39** |
| **Far** | **433** |  | **7.78** | **9.38** | **0.73** |

Fig. 6. Measured PTE of the MSWPT system without and with the MTM slabs .

Here, the real value of the is designed to be -1.02 at 6.78 MHz which means it has an approximate value of -1.02. The imaginary value of the is 0.02, which means it has a low magnetic loss. As for 433 MHz WPT, the real value of is designed to have near zero values in the range of 425.6 to 457.5 MHz . This means the MTM slabs can change the direction of electromagnetic field at the boundary to negative and near zero, thereby enhancing the PTE of the WPT for both 6.78 MHz and 433 MHz. The simulation results are shown in Fig. 4.

1. Fabrication and Measurement Results

As shown in Fig. 5, the MTM-based MSWPT is fabricated and the PTE is measured in an anechoic chamber. For measurement, a vector network analyzer (HP E8361A, Agilent, Inc.) is used. The PTE is obtained using the following equation:

(1)

We measure the PTE of the MSWPT with and without the MTM slabs. The PTD ranges from 0 to 300 cm. As shown in Fig. 6, the WPT with the MTM slabs shows improved PTE for all distances except for 10 cm in the near-field scale which means the MTM slabs focus magnetic fields effectively, thereby increasing the PTE. The PTE of the WPT with the MTM slabs at a distance of 50 cm is improved from 5.42 % to 50.12 % (a factor of 9.25). However, the PTE at a distance of 140 cm drops below 1 % even with the MTM slabs inserted. In addition, the PTE of the radiative WPT outperforms that of the resonant coupling WPT from a distance of 90 cm (cross-over point) and shows stable PTE within the far-field scale. Especially, the WPT with MTM slabs shows better PTE compared with the WPT without MTM slabs for all distances in the far-field scale with the improved Tx/Rx antenna gain. The calculated gain of the Tx/Rx antennas using a Friis equation is shown to be improved from 5.86 dBi to 8.91 dBi. The demonstrated WPT architecture with MTM slabs can deliver approximately 4.07 times as much power as the WPT without MTM slabs in the far-field scale. Based on the PTE measurement results, the PTD scale can be categorized into three regions. A blue area (0 ~ 70 cm) in Fig. 6 can be classified as the near-field WPT zone. As the resonant coupling WPT mode outperforms the radiative WPT mode in the region, the MSWPT will be operated as the resonant coupling WPT mode. A gray area (70 ~ 110 cm) can be classified as a buffer zone. In this region, the WPT modes should be switched because the radiative WPT starts to outperform the resonant coupling WPT at the cross-over point. A red area (110 cm ~) can be classified as the far-field zone. As the radiative WPT mode outperforms the resonant coupling WPT mode in this region, the MSWPT would be operated as the radiative WPT mode.

It is concluded that the transition from 6.78 MHz near-field WPT to 433 MHz far-field WPT is advantageous in the MSWPT when the distance is greater than 90 cm and the MSWPT enables to transfer wireless power seamlessly regardless of PTD owing to its multi-scale feature.

The MTM-based MSWPT is compared with other reported MTM based WPT systems, as shown in Table. 1. For comparison, the transfer distance between Tx and Rx coils are normalized to the diameter of the Tx coil as shown in Eq. (2).

(2)

where , , and are the distance, normalized distance, and Tx coil diameter, respectively. In addition, a figure of merit (FoM) has been introduced to compare those WPT systems considering the PTD, the coil size, and the PTE [13]:

(3)

The MTM-based MSWPT system has shown overall improved PTEs compared to other work. It should be noted that this is the first system enabling both near-field and far-field scale WPT in a single device with successful demonstration of seamless WPT in multi-scale zones.

1. Conclusion

This work demonstrates a high efficiency MTM-based MSWPT system for smart home applications. The experimental results show that the MTM-based WPT system is capable of transferring wireless power efficiently in the near-field and far-field scales. It is expected that the introduced WPT system will open new possibilities for smart home WPT applications with increased PTE and PTD in various scenaries.

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