High Efficiency Multiscale Wireless Power Transfer System Using Metasurface Slabs

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ABSTRACT
In this work, a highly efficient metasurface-based multi-scale wireless power transfer (MSWPT) system is presented. The MSWPT is designed to work as a near-field WPT at 6.78 MHz (AirFuel Alliance standard frequency) and far-field WPT at 433 MHz (ISM band for household devices) according to its power transfer distance (PTD). This property that can function in both near-field scale and far-field scale is defined as multi-scale property in this paper. The metasurface slabs which have an electromagnetic (EM) wave focusing characteristic for both frequency bands are integrated with the transmitter (Tx) and receiver (Rx) coils to enhance the power transfer efficiency (PTE) of the MSWPT. The metasurface-based MSWPT system is characterized and measured for both near-field and far-field scales. The measured results exhibit that the PTE of the MSWPT is improved from 5.4 % to 50.1 % with the metasurface slabs at a PTD of 50 cm (near-field scale at 6.78 MHz), i.e. 9.3 times improvement while the PTE at a PTD of 140 cm (far-field scale at 433 MHz) is improved from 2.3 % to 9.4 % with the metasurface slabs, i.e. 4.1 times improvement. In addition, the PTE measurements with the lateral and angular misalignment conditions in the MSWPT system are investigated for practical applications. Results show that the metasurface slabs enhance the PTE of the MSWPT even in the misaligned condition.

INDEX TERMS
Wireless power transfer (WPT), metamaterials, metasurfaces, multi-scale WPT (MSWPT), power transfer efficiency (PTE), misalignment.

I. INTRODUCTION
In recent years, wireless power transfer (WPT) technologies have gained lots of attention with the growing demand for wireless charging in contemporary electronics. The WPT refers to the transmission of electrical energy without wires as a physical link. In general, the WPT technology can be categorized into two classifications, near-field WPT and far-field WPT. The near-field WPT refers to a WPT that transfers energy wirelessly over a power transfer distance (PTD) shorter than its operating wavelengths. The most broadly utilized technologies belonging to this classification are inductive coupling-based WPT and magnetic resonant coupling (MRC)-based WPT. But the most critical limitation of the near-field WPT is the power transfer distance (PTD). Although the MRC-based WPT further expands the PTD to a mid-field range PTD (cm ~ m), the extension of the PTD decreases the coupling between the transmitter (Tx) and receiver (Rx) coils, thereby greatly decreasing power transfer efficiency (PTE) of the WPT and restricting the PTD of the MRC-based WPT [1]. As regards the far-field WPT, microwave power transfer, also known as radiative WPT, falls into this classification. The power radiated from the Tx antenna transmits across a far distance through the air. Then, the Rx antenna captures this electromagnetic (EM) wave. However, as microwaves propagate in omni-directions, the far distance transmission suffers from substantial path losses, resulting in comparably low PTE.

Recently, researchers have studied that metasurfaces can be used to magnify the PTE of the near-field WPT [2]. Metasurfaces are two-dimensional metamaterials, which are artificially designed materials that exhibit unusual EM characteristics, such as negative refraction and evanescent wave amplification, thereby improving the PTE [3]. The metasurfaces are commonly used to enhance the PTE of the near-field WPT by inserting one or more metasurface slabs between Tx and Rx coils [4]–[11]. However, the critical problem is that some previously studied metasurface slabs are too huge and bulky in geometry, restricting the practical applicability of metasurface slabs [4], [5], [10]. If the additional bulky
metasurface slabs are inserted to the transmission path, it constrains the flexibility and usefulness of the metasurface-based WPT. Furthermore, even though the metasurface slabs further extend the working PTD of the WPT systems, the PTD of the reported metasurface-based WPT systems is still limited, imposing constraints on their practical applicability. Meanwhile, in the area of far-field WPT, metasurfaces have been introduced for the antenna gain enhancement as a form of metasurface superstrates [12]–[15], where metasurface focus the EM fields thereby enhancing the gain of the antenna. In [15], a dual functional antenna inspired by metasurface for both wireless communications and WPT has been demonstrated. But only a single Rx part has been investigated, not a complete WPT system. In addition, only a PTE for low frequency band (6.78 MHz) has been demonstrated.

In this paper, we report a high efficiency metasurface-based multi-scale WPT (MSWPT) system using that can work for both the near-field scale at 6.78 MHz AirFuel Alliance standard frequency and the far-field scale at 433 MHz ISM band for household devices for WPT. This property that can function in both near-field scale and far-field scale is defined as multi-scale property in this paper.

This paper is an expanded work of the preliminary study [16]. Compared with [16], more discussions and results are reported including the followings: 1) the detailed theoretical analysis, 2) parametric analyses that support the theoretical analysis, 3) the studies on the effects of the number of metasurface unit cells on the performance of the MSWPT, 4) the studies on the effects of the misalignments between the Tx and Rx coils for the practical applications, and 5) the detailed comparison of the MSWPT with previously studied metasurface-based WPT systems.

II. DESIGN AND ANALYSIS OF THE MULTI-SCALE WPT SYSTEM

The concept of the metasurface-based MSWPT is shown in Fig. 1. The MSWPT operates as both near-field and far-field WPT simultaneously. Therefore, the operating frequency of the MSWPT system can be chosen according to the location of the Rx. If the Rx is placed in the near-field scale, the MSWPT works in the MRC-WPT mode at 6.78 MHz. With the metasurface slabs, the PTE of the MSWPT is greatly increased in the near-field. But, as the PTD increases, the PTE of the MSWPT system decreases substantially even with the metasurface slabs. In order to compensate this problem, the radiative WPT mode at 433 MHz can be chosen when the Rx is placed outside the boundary of the near-field scale which is in the far-field scale. This characteristic is defined as multi-scale property in this paper.

The geometry of the MSWPT system is depicted in Figure 2. Firstly, the 4-coil WPT system which consists of a source coil, Tx coil, load coil, and Rx coil is presented and the 4-coil WPT system is integrated with two at the front side of the Tx and Rx coils, the PTE of the WPT for both scales can be substantially enhanced. 3) The metasurface slabs are inserted at the front sides of the Tx and Rx coils which are much more appropriate for the practical WPT applications.

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identical metasurface slabs at the front sides of the Tx and Rx coils. The detailed configurations of the metasurface unit cell, Tx/Rx coils, and source/load coils are depicted in Fig. 3 (a), (b), and (c), respectively.

A. MULTI-SCALE PROPERTY

The multi-scale feature of the MSWPT system is realized by the capacitors that are connected to the Tx, Rx, and metasurface unit cell (Fig. 3 (a) and (b)). Fig. 4 (a) shows the equivalent circuit of the Tx, Rx, and metasurface unit cell which includes a self-inductance ($L_T$), ohmic loss ($R_{Ohm}$), resistance ($R_0$) caused by the connected capacitor ($C_0$), parasitic self-capacitance ($C_{par}$), and the dielectric loss ($R_d$). This equivalent circuit can be simply expressed by an RLC circuit model as depicted in Fig. 4 (b). In this work, we utilize the characteristic of capacitive reactance in the radio frequency (RF) circuit. The connected capacitor ($C_0$) has a relatively high capacitance value compared with parasitic self-capacitance ($C_{par}$). The differences in the capacitance values enable the MSWPT to have a multi-scale property. The following equations can be used to obtain the capacitive reactance of the equivalent circuit and connected capacitor:

$$\frac{1}{X_C} = \frac{1}{X_{C_{par}}} + \frac{1}{X_{C_0}}$$  \hspace{1cm} (1)

$$X_{C_0} = \frac{1}{2\pi f C_0}$$  \hspace{1cm} (2)

$$X_{C_{par}} = \frac{1}{2\pi f C_{par}}$$  \hspace{1cm} (3)

where $X_C$, $X_{C_{par}}$, and $X_{C_0}$ are the capacitive reactance of the resultant capacitive circuit, $C_{par}$ and $C_0$, respectively, and $f$ is the working frequency. According to the Eq. (2), the $X_{C_0}$ will be determined depending on its working frequency and the value of the connected capacitor. If the operating frequency is relatively high such as 433 MHz, $X_{C_0}$ (Eq. 2) becomes extremely small as both $f$ and $C_0$ terms are very high which implies that the connected capacitor is shorted. It reflects that when the operating frequency is 433 MHz, the resonant frequencies of the Tx, Rx, and metasurface unit cells are not changed by the connected capacitors, but decided by the inherent coil/metasurface structures, their dimensions, and configurations, i.e. $L_T$, $R_T$, and $C_{par}$ in the circuit (Fig. 4 (b)).

Meanwhile, in the comparably low frequency range such as 6.78 MHz, $X_{C_0}$ cannot be ignored as the value of the $f$ is small. Thus, the resonant frequencies of the metasurface, and Tx, Rx coils can be adjusted by changing the value of the connected capacitor. This characteristic of the capacitive reactance in a distinct frequency scale is manipulated for the functioning of the multi-frequency based self mode-selective MSWPT. Once the geometries of the Tx, Rx and, metasurface unit cells are decided for the far-field scale, the values of the connected capacitors are carefully chosen for the MRC operation in the near-field scale. By utilizing this characteristic, the metasurface-based MSWPT system is designed to have multi-scale WPT functions for both 6.78 MHz and 433 MHz.

B. DESIGN OF THE 4-COIL WPT SYSTEM

First, the 4-coil WPT system is designed as depicted in Fig. 3 (b) and (c). The WPT system includes the source coil, Tx coil, load coil, and Rx coil. The thickness of the acrylic substrate ($\varepsilon_r = 3.5$) is 1 mm.

For the validation of the multiscale property, the parametric analysis is carried out using EM simulator called High Frequency Structure Simulator (HFSS, Ansys Inc.). Firstly, the dimension and structure of the Tx/Rx are designed to operate at 433 MHz. Then, the value of the connected capacitor is varied from 120 to 320 pF while keeping the dimension of the Tx/Rx. The lumped RLC boundary has been utilized for implementing the connected capacitor in HFSS. As depicted in Fig. 5 (b), the resonant frequencies of the Tx/Rx with the
varied capacitor values are all the same in the high frequency scale (433 MHz). Because the connected capacitor acts like a short circuit, the resonant frequencies of the Tx/Rx are not affected by the connected capacitor. However, in the low frequency scale (6.78 MHz), the resonant frequency of the Tx/Rx can be tuned by modifying the value of the connected capacitor as shown in Fig. 5 (a). Using this analysis, the multi-scale feature of the Tx/Rx can be realized. On the basis of the parametric simulation results, a 220 pF capacitor is selected and connected parallelly to Tx/Rx. The simulated and measured return losses of the Tx/Rx for the near-field scale and far-field scale are depicted in Fig. 6 (a) and (b), respectively. The return losses are measured by using a vector network analyzer (HP E8361A, Agilent, Inc.) after short-open-load calibration. The results show that the 4-coil WPT system exhibits a multi-scale property. In addition, the measured and simulated return losses of the WPT system are almost identical.

C. DESIGN OF THE METASURFACE SLAB

As regards the metasurface design, a 3-turns square spiral shaped resonator is used for the unit cell as it has a relatively higher Q-factor compared with a split ring resonator (SRR) [17]. The metasurface unit cells are realized on a polyethylene (PE) substrate due to its thin thickness and low loss tangent. The metasurface unit cell is engineered to have a multi-scale property for 6.78 MHz and 433 MHz which means the metasurface has a beam focusing property for both frequency bands. Thus, when the metasurface slabs are located at the front of the Tx/Rx coils, they can help the WPT system to have better PTE with the negative and near zero refractive property of the metasurface slab. To verify the beam focusing characteristic of the metasurface, the effective refractive index for both frequency bands are simulated which can be calculated using the following standard retrieval methods [18]–[20].

\[
z = \pm \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}
\]

\[
n_{\text{eff}} = \frac{1}{k_0d} \left[ \left[ \text{Im}(e^{i\pi k_d}) \right]^r + 2m\pi \right] - i\left[ \text{Im}(e^{i\pi k_d}) \right]^r
\]

\[
e^{i\pi k_d} = \frac{S_{21}}{1 - S_{11} \frac{z''}{z'}}
\]

\[
\mu_{\text{eff}} = n_{\text{eff}} z
\]

where \( z \) is the impedance; \( S_{11} \) and \( S_{21} \) are the reflection and transmission coefficients; \( d \) is the thickness of the slab at its thickest point; \( (\cdot)^r \) and \( (\cdot)^i \) indicate the real part and imaginary.
FIGURE 8. Simulation results of the metasurface unit cell: (a) Effective permeability result for near-field scale (6.78 MHz), (b) Effective refraction index result for far-field scale (433 MHz).

part of the complex numbers; $n_{eff}$ is the effective refraction index; $k_0$ is the wavenumber; ; $m$ is the integer associated with the branch index of $n'$; and $\mu_{eff}$ is the effective permeability.

In this work, the refractive indexes of the metasurface for 6.78 MHz and 433 MHz are carefully designed. Especially, the ways of determining the effective refractive index in two distinct frequencies are disparate each other. Normally, in order to obtain an effective refractive index of the metasurface, both effective permittivity $\varepsilon$ and permeability $\mu$ are necessary. But in the case of near-field WPT (6.78 MHz), the electric and magnetic field decouple each other in a deep subwavelength limit so that only effective permeability is utilized to calculate an effective refractive index. In the meantime, as regards the far-field WPT (433 MHz), the entire system size is not much smaller than its operating wavelength, which does not come under the deep subwavelength condition. Thus, both effective permeability and permittivity are needed for the determination of an effective refractive index of the metasurface in the far-field WPT scale.

The multi-scale characteristic of the metasurface unit cell is also analyzed parametrically by utilizing HFSS. First, the dimension of the metasurface unit cell is engineered to show near zero refraction index for 433 MHz. After that, the value of the connected capacitor is varied from 350 to 550 pF while keeping the dimension of the metasurface unit cell. As depicted in Fig. 7 (b), the values of the effective refraction index in the high frequency scale (433 MHz) are almost the same even when the capacitor values are varied since the connected capacitor acts like short circuit. However, in the low frequency scale (6.78 MHz), the values of the effective permeability can be changed by sweeping the value of the connected capacitor as depicted in Fig. 7 (a). On the basis of the parametric analysis, a 450 pF capacitor is parallely connected to each metasurface unit cell for the multi-scale property. As shown in Fig. 8 (a), the real part of the $\mu_{eff}$ is $-1.02$ at 6.78 MHz. It indicates that it has an effective refractive index value of $-1.02$ at 6.78 MHz. In addition, the metasurface has the imaginary part of the effective permeability of 0.02. It implies that the designed metasurface has a low magnetic loss at 6.78 MHz. As for far-field WPT case (433 MHz), the real part of effective refractive index is carefully engineered to exhibit near zero values ($n_{eff} (re) \leq 0.5$) in the frequency range of 425.6 to 457.5 MHz as depicted in Fig. 8 (b). It indicates that the metasurface slabs have the beam-focusing property, thereby changing the direction of EM field at the boundary to negative and near zero. Therefore, the PTE of the MSWPT for both 6.78 MHz and 433 MHz can be significantly improved.

Then, the $2 \times 2$ metasurface slabs are inserted at the front side of the Tx/Rx with the separation, $s$, as shown in Fig. 2. For the practical applications, the close distance is preferred. However, the coupling coefficient between the Tx/Rx and metasurface slab is increased when they get closed each other, which results in the shift of resonance frequency. Therefore, the minimum value of the separation should be chosen without degrading the impedance matching at resonance frequency. In this work, the separation of 10 mm is chosen which is the closest distance not much degrading the impedance matching at both 6.78 MHz and 433 MHz.

III. FABRICATION AND MEASUREMENT RESULTS

The metasurface-based MSWPT is fabricated, measured, and characterized. Fig. 9 shows the fabricated metasurface and Tx/Rx. Fig. 10 shows the measurement setup in an...
FIGURE 10. Measurement setup for the metasurface-based MSWPT system in an anechoic chamber.

For the PTE measurement, we utilize a vector network analyzer (HP E8361A, Agilent, Inc.). The PTE can be extracted from the measurement data by using the following equation [22]:

\[ PTE = |S_{21}|^2 \times 100\% \]  \hspace{1cm} (8)

A. MEASUREMENT OF PTE

In this section, the PTE of the MSWPT with and without the metasurface slabs is measured as a function of PTD that ranges from 0 to 340 cm. The metasurface slabs consist of \(2 \times 2\) metasurface arrays. The PTE of both near-field WPT mode (6.78 MHz) and far-field WPT mode (433 MHz) are measured separately.

As depicted in Fig. 11, the MSWPT with the metasurface slabs exhibits enhanced PTE for entire PTDs except for 10 cm (threshold distance) in the near-field WPT mode (6.78 MHz), indicating that the inserted metasurface slabs concentrate and amplify the magnetic fields, hence enhancing the PTE of the MSWPT. At a PTD of 50 cm, the PTE increases from 5.4\% to 50.1\% which is a factor of 9.3 improvement when the metasurface slabs are inserted. But, as the PTD increases to 140 cm, the PTE of the MSWPT decreases below 1\% even with the metasurface slabs placed. Furthermore, the PTE of the radiative WPT mode (433 MHz) starts to get higher than that of the MRC-WPT mode (6.78 MHz) from a PTD of 90 cm (cross-over point). The MSWPT in the radiative WPT mode exhibits steady PTE within the far-field scale. It is notable that the MSWPT with metasurface slabs exhibits superior PTE compared with the MSWPT without metasurface slabs for entire PTDs within the far-field scale with the enhanced antenna gain. The improved gain can be obtained using the following Friis equation:

\[ P_r = \frac{G_t G_r \lambda^2}{(4\pi r)^2} P_t \]  \hspace{1cm} (9)

where \(P_t\) and \(P_r\) are the transmitted and received RF power; \(G_t\) and \(G_r\) are the Tx and Rx antenna gain; \(\lambda\) is the wavelength; \(r\) is the transfer distance. According to Eq. (9), the measured gain of the Tx/Rx antennas is enhanced from 5.86 dBi to 8.91 dBi when the metasurface slabs are inserted. It indicates that the MSWPT system with metasurface slabs is capable of transferring 4.1 times as much power as the MSWPT without metasurface slabs in the radiative WPT mode.

On the basis of the measurement results in Fig. 11, the PTD is classified into three different regions. First, an area colored by blue (0 ~ 70 cm) in Fig. 10 is categorized as the near-field WPT zone. In this area, the MSWPT functions as the MRC-WPT mode since the MRC-WPT mode exhibits better PTE performance than the radiative WPT mode. Second, a gray region (70 ~ 110 cm) is categorized as a transition zone. In this zone, the MSWPT modes have to be switched from the MRC-WPT mode to the radiative WPT mode as the radiative WPT begins to surpass the MRC-WPT from the cross-over point (90 cm). Finally, a red region (110 cm ~) can be categorized as the far-field zone. In this zone, the MSWPT will be functioned as the radiative WPT mode since the performance of the radiative WPT mode surpasses that of the MRC-WPT mode.

The measurement results indicate that the WPT mode transition from the near-field MRC-WPT (6.78 MHz) to 433 MHz far-field microwave WPT (433 MHz) is beneficial in the MSWPT when the PTD is farther than the cross-over point. It means that the MSWPT is capable of transferring wireless power seamlessly regardless of PTD due to its multi-scale characteristic.

B. EFFECTS OF THE NUMBER OF METASURFACE UNIT CELLS ON THE PTE

In this section, the effects of the number of metasurface unit cells on the PTE are investigated. We measure and compare the PTE of the MSWPT with \(1 \times 1, 2 \times 2, 3 \times 3\) metasurface slabs, and without metasurface slabs in the near-field and far-field scales. As depicted in Fig. 12 (a) and (b), the PTE of the MSWPT with the \(2 \times 2\) metasurface slabs exhibits the highest PTE and followed by the PTE of the MSWPT with the \(3 \times 3\) metasurface slabs and that with \(1 \times 1\) slab, and that without metasurface slabs for both scales. However, the increased PTE of the WPT with \(1 \times 1\) metasurface slabs is...
much smaller than that with $2 \times 2$ and $3 \times 3$ metasurface slabs. As only one metasurface unit cell is utilized, the EM waves could not be effectively focused when they pass the $1 \times 1$ metasurface slabs. Interestingly, the PTE of the MSWPT with the $3 \times 3$ metasurface slabs shows worse PTE than that with the $2 \times 2$ metasurface slabs. If the number of metasurface unit cells in the array increases from $2 \times 2$ to $3 \times 3$, the EM beam focusing coverage is expected to be expanded. Unlike the expectation, the PTE improvement could not be achieved using $3 \times 3$ metasurface slabs as the beam focusing coverage of the $2 \times 2$ metasurface slabs is already enough to cover the size of the Tx and Rx coils.

Moreover, the experimental result indicates that the $3 \times 3$ metasurface slabs have increased loss compared with the $2 \times 2$ metasurface slabs thereby degrading the PTE of the MSWPT system. On the basis of the analysis in this section, the optimal number of the metasurface unit cell in the array for the MSWPT is determined to be $2 \times 2$. In addition, for the comprehensive understanding of the effects of the number of metasurface unit cells on the far-field MSWPT, the radiation patterns of the MSWPT system without and with $1 \times 1$, $2 \times 2$, $3 \times 3$ metasurface slabs are simulated as shown in Fig. 13. The result shows the consistent tendency with the measured PTE in Fig. 12.

In addition to the number of metasurface unit cells, the gap between unit cells should be carefully determined. This gap is closely related to the mutual inductance between the unit cells and the magneto-inductive waves (MIWs). As the metasurface unit cells in the array are close to one another, a current circulating one unit cell generates a strong magnetic flux through the neighboring unit cells thereby inducing the mutual inductance between them. If a resonant current is induced in one cell and the mutual inductance leads to a current being excited in the neighboring unit cells. These in turn inspire their neighbors resulting in the propagation of MIWs [23]. On the basis of the assumption that only the interaction between adjacent metasurface unit cells is affecting MIW propagation, the dispersion equation of a 2D array of metasurface unit cells is given by [23]

$$\frac{\omega_0}{\omega} = (1 + k_x \cos (\gamma_x a) + k_y \cos (\gamma_y a))^\frac{1}{2}$$

where $a$ is the lattice constant of the array which is the distance between the centers of two adjacent unit cells; $k_x$ and $k_y$ are coupling coefficients of the metasurface unit cells in the $x$ and $y$ directions, respectively; $\gamma_x$ and $\gamma_y$ are the complex propagation constants of MIWs. For $|\gamma_x a|, |\gamma_y a| \ll 1$, they describe propagating MIWs. The important role of the MIWs in WPT systems is that the incident evanescent waves coming from the Tx coil strongly couple to the fields generated by MIW at the MTM interface and take energy from them, amplifying the evanescent waves, thereby enhancing the PTE of the WPT systems. In the aspect of the metasurface unit cell design, the lattice constant is directly related to the gap between the metasurface unit cells and coupling coefficients. Moreover, the coupling coefficient also affects the operating frequency of the metasurface unit cells. Therefore, the dimension of the unit cell and the gap between the unit cells should be carefully determined without degrading the performance of the metasurface while maintaining the operating frequency of the WPT system. In this work, the gap between the metasurface unit cells is chosen to be 10 mm for design simplicity. Then, the remaining design parameters are determined for the metasurface unit cell to work at both 6.78 MHz and 433 MHz according to the procedure described in Sec II. A.
C. PTE MEASUREMENT OF THE MISALIGNED MSWPT

In practical WPT applications, the perfect alignment between the Tx and Rx is very difficult to achieve. Definitely, the PTE of the WPT is greatly affected by the misalignments in the WPT system. Therefore, to move further into the practical WPT applications, the WPT system must consider the misalignment effects, and countermeasures to compensate the degraded PTE owing to the misalignment conditions.

In this section, the effects of the misalignments on the PTE of the MSWPT have been studied. We investigate the effects of the lateral and angular misalignment on the PTE of the proposed MSWPT system without and with the metasurface slabs at a PTD of 30 cm (near-field scale) and 140 cm (far-field scale). In Fig. 14 (a) and (c), as the misaligned lateral distance \( D_L \) increases, the PTE of the MSWPT is degraded for both cases (with and without the metasurface slabs). However, it is noticeable that the PTE of the MSWPT increases substantially for entire PTEs in both scales when the metasurface slabs are inserted. In addition, the studies of the angular misalignment \( \theta \) are also exhibited in Fig. 14 (b) and (d). The PTE of the MSWPT without and with the metasurface slabs decreases as the angle of the Rx becomes larger. It is shown that the impacts of the metasurface slabs on the PTE of the MSWPT degraded as the angular misalignment becomes severe. Particularly, the enhanced PTE owing to the metasurface slabs is close to 0% when the misaligned angle is 90°. This indicates that the EM waves radiated by the Tx cannot be captured by the Rx when the Rx coil is perpendicular to the Tx even though the EM waves are amplified and concentrated by the metasurface slabs. The efficiency difference between 0° and 90° can also be demonstrated by the cross-polarization which is the difference between the maximum radiation intensity of the required polarization (co-polarization) and cross-polarization.

However, it is concluded that the metasurface slabs effectively mitigate the impacts of the misalignments on the MSWPT system for all other cases.

D. MEASUREMENT COMPARISON

In this section, the metasurface-based MSWPT is compared with previously studied metamaterial or metasurface based WPT systems. For the fair comparison, the PTD (distance between Tx and Rx) and the working distance (distance between Rx and metasurface) are normalized to the geometrical mean of Tx, Rx, and metasurface slab size as described in the following equation:

\[
D_{\text{norm}} = \frac{D}{\sqrt{n^2 d_T \cdot d_R \cdot d_M}}
\]

where \( D_{\text{norm}} \), \( D \), \( d_T \), \( d_R \), \( d_M \), and \( n \) are the normalized distance, distance, Tx diameter, Rx diameter, largest dimension of the metasurface slab (length or width), and the number of metasurface slabs, respectively. Moreover, a figure of merit (FoM) has been utilized in order to compare those metasurface-based WPT systems taking the PTE, the coil and
TABLE 1. Comparison of this work with other metamaterial or metasurface based WPT systems.

| Ref. | Operating frequency (MHz) | $d_r$ ($d_\theta$) (mm) | $d_M$ (mm) | Property of metamaterial or metasurface | Configuration of the metamaterial or metasurface / # of slabs | Transfer /working distance (mm) | Normalized transfer/working distance | Multi-scale property | PTE with metamaterial or metasurface (%) | Figure of merit |
|------|--------------------------|------------------------|------------|----------------------------------------|------------------------------------------------|-----------------------------|-----------------------------|------------------|--------------------------------------|----------------|
| [4]  | 27                       | 400                    | 585        | $\mu_{eff} = -1$                       | Double sided / 2                                | 500 / 240                   | 1.03 / 0.5                 | $\times$          | 47                                   | 0.49            |
| [5]  | 6.5                      | 600                    | 700        | Negative $\mu_{eff}$                   | Single sided / 2                                | 1000 / 500                  | 1.54 / 0.77                 | $\times$          | 45                                   | 0.69            |
| [6]  | 7.43                     | 150                    | 260        | $\mu_{eff} = 0, -1$                    | Double sided / 1                                | 200 / 165                   | 1.11 / 0.92                  | $\times$          | 18.6                                 | 0.21            |
| [7]  | 26.65 $^{T_x=50,}$ $^{R_x=36}$ | 69                    |            | $\mu_{eff} = -1$                       | Double sided / 1                                | 79 / 50                     | 1.58 / 1                    | $\times$          | 18.23                                | 0.29            |
| [8]  | 5.57                     | 40                     | 60         | $\mu_{eff} = -1$                       | 3D structure / 1                                | 40 / 10                     | 0.82 / 0.2                   | $\times$          | 35                                   | 0.29            |
| [9]  | 6.78                     | 600                    | 750        | $\mu_{eff} = 1, -1$                    | Single sided / 1                                | 900 / 450                   | 1.54 / 0.67                  | $\times$          | 63.04                                | 0.84            |
| [10] | 3                       | 500                    | 600        | $\mu_{eff} = -1$                       | Single sided / 2                                | 800 / 560                   | 2.4 / 1.02                   | $\times$          | 72.05                                | 1.05            |
| [11] | 472.6                    | 36                     | 80         | High $\varepsilon_{eff}$               | Single sided / 2                                | 38 / 4                      | 1.67 / 0.07                  | $\times$          | 60.8                                 | 0.43            |

This work

Near-field $6.78$ $180$ $300$ $\mu_{eff} = -1$ Single sided / 2 $500 / 10$ $2.78 / 0.06$ $\bigcirc$ $50.1$ $1.08$

Far-field $433$ $180$ $300$ $\eta_{eff} \cong 0$ Single sided / 2 $1400 / 10$ $7.78 / 0.06$ $\bigcirc$ $9.4$ $0.57$

metasurface size, and the PTD into consideration [24]:

\[ FoM = D_{\text{norm}} \times \text{PTE} \]  

(12)

As shown in Table 1, the demonstrated metasurface-based MSWPT system has exhibited improved PTEs compared to previously reported studies on the whole. In addition, the working distance of the metasurface-based MSWPT is much smaller compared to those of earlier studies. It implies that the demonstrated MSWPT is more suitable for practical WPT systems. Especially, it is worth emphasizing that this is the firstly reported WPT system functioning both near-field and far-field scale WPT in a single system with a successful demonstration of transferring wireless power seamlessly in multi-scale regions.

IV. CONCLUSION

In this paper, a highly efficient metasurface-based MSWPT system is reported. The measurement results prove that the metasurface-based WPT system can operate in both near-field and far-field scale WPT in a single system. The measured results exhibit that the PTE of the MSWPT is improved from 5.4 % to 50.1 % with the metasurface slabs at a PTD of 50 cm (near-field scale at 6.78 MHz), i.e. 9.3 times improvement while the PTE at a PTD of 140 cm (far-field scale at 433 MHz) is improved from 2.3 % to 9.4 % with the metasurface slabs, i.e. 4.1 times improvement. Moreover, the effects of the number of metasurface unit cells on the PTE of the MSWPT are investigated. Furthermore, the PTE measurement in the misaligned condition proves that the metasurface slabs enhance the PTE of the MSWPT even in the misaligned condition. It is highly anticipated that the reported metasurface-based MSWPT will open up new possibilities for practical WPT applications with enhanced PTE and PTD in various conditions.

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