Highly efficient mmWave based far-field wireless power transfer system using metaconductors

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***Abstract*—In this project, highly efficient wireless power transfer (WPT) using metaconductors is investigated. First, to suppress the skin effect at the mmWave frequencies, metaconductors consisting of non-ferromagnetic and ferromagnetic metal layers are exploited. Especially, a Cu/Co metaconductor-based rectenna for mmWave WPT applications is demonstrated for the first time. Second, to further reduce the loss of the WPT system, a low-loss glass wafer is employed as a rectenna substrate. As a test vehicle, a highly energy-efficient transmitter (Tx) antenna and receiver (Rx) antenna, and rectifier circuit are demonstrated.**

***Index Terms*—Wireless power transfer (WPT), metaconductor, high efficiency, power transfer efficiency (PTE).**

I. Introduction

RECENTLY, wireless power transfer (WPT) technologies have gained lots of attention with the growing demand for wireless charging in contemporary electronics. WPT refers to the transmission of electrical energy without wires as a physical link. In general, WPT technology can be categorized into two classifications, near-field WPT and far-field WPT. The near-field WPT refers to transferring 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 limited 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.

In the radiative WPT system as shown in Fig. 1, radiative power radiates from a Tx propagating over a long distance, is received by an Rx, then converted to DC, and stored in a battery. The entire efficiency of the WPT system, η_{sys} , is described as $\eta_{sys} = \eta_1\eta_2\eta_3 = P_{out}/P_{in}$ (Eq. 1), where $\eta_{sys}, \eta_1, \eta_2$, and η_3 are the entire system efficiency, DC to RF conversion efficiency, RF transmission efficiency, RF to DC conversion efficiency, respectively; P_{in} and P_{out} are the input and output DC power. The current state-of-the-art end-to-end efficiency (η_{sys}) for far-field WPT systems is estimated to be

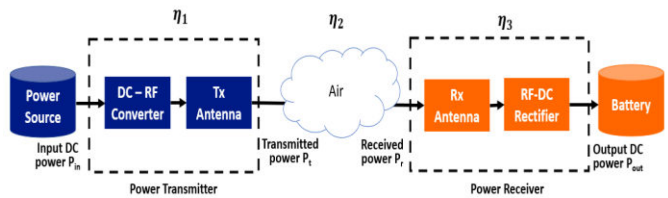

Fig. 1. Block diagram of radiative WPT system

in the range of 3% to 5% [1]. Unfortunately, this low efficiency greatly hinders the practical exploration of the far-field WPT. Moreover, because most conventional far-field WPT systems have utilized low gigahertz frequencies [2], e.g. < 3 GHz, the Tx/Rx antennas are quite big, and often the dimension of a directional antenna becomes a few meters in diameter, making it less practical. Also, less directive antennas cause the path loss to be significant over a far distance e.g. ~ km, thereby resulting in low end-to-end efficiency.

To mitigate these issues, mmWave-based WPT can be considered. As its wavelength is small (~ mm), the corresponding antenna size can be reduced. It is less dispersive and beam directivity can be high thus the path loss can be lowered. However, a limiting factor in the use of mmWave for WPT is its high RF conductor loss associated with the skin effect which causes high RF resistance and low efficiency of the WPT system. Therefore, in this research project, the end-to-end efficiency improvement of the mmWave-based far-field WPT system is addressed from the following two aspects:

1. Low loss metaconductors (MCs): Utilization of the multi-layer non-ferromagnetic / ferromagnetic conductors as eddy current canceling conductors.
2. Low-loss glass substrate: reduction of substrate losses using the low-loss glass substrate.

II. Metaconductor-based WPT

A metaconductor consists of multiple nanolayers of ferromagnetic and non-ferromagnetic materials (metals). The positive magnetic permeability of the non-ferromagnetic layers will cancel out the negative magnetic permeability of the ferromagnetic layers at the frequencies between ferromagnetic resonance (FMR) and anti-ferromagnetic resonance (AFMR) of the ferromagnetic materials, resulting in eddy current

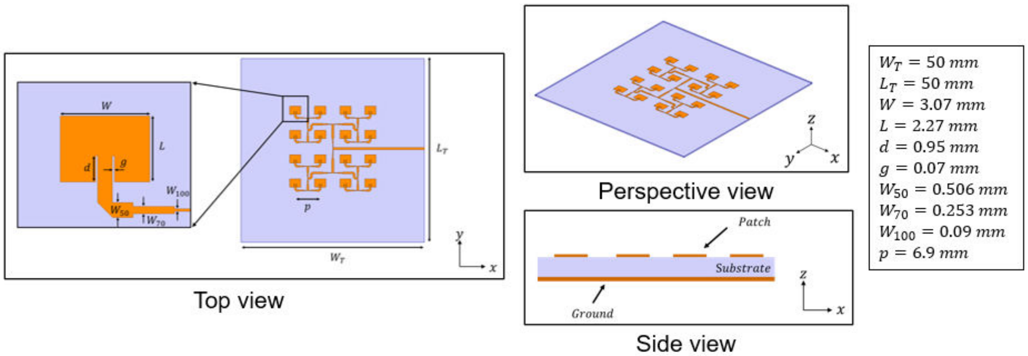

Fig. 2. Schematic of the Tx and Rx.

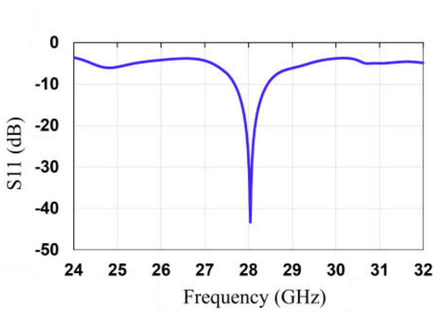

Fig. 3. Simulated S11 of the Tx and Rx.

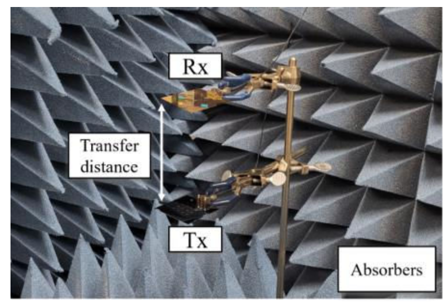

Fig.4. Fabricated metaconductor-based WPT and measurement setup.

cancellation and therefore skin effect suppression [3].

With such a metaconductor mechanism, a 28 GHz Cu/Co metaconductor based far-field WPT system is designed, simulated, and characterized. The proposed WPT system consists of a 16-element array Tx antenna, Rx antenna, and rectifier circuit. The Tx and Rx antennas, feeding lines, and rectifier lines are fabricated using 10 pairs of Cu/Co metaconductor (total 1.85 µm thick) on a 300 µm thick low loss glass substrate (SW 3.4, Corning Inc.), thereby decreasing the conductor loss and substrate loss, and thus increasing the gain of the antenna.

As shown in Fig. 2 and 3, a 16-element array antenna is designed and simulated using HFSS (High Frequency Structure Simulator, ANSYS Inc.), with a resonance frequency of 27.9 GHz, a 10-dB bandwidth of 0.78 GHz, and a simulated gain of 16.2 dBi.

III. Fabrication and Measurement Results

The proposed MC-based WPT system is fabricated on a 0.3 mm thick low-loss glass substrate (SG 3.4, Corning Inc.). In addition, we measure the transmission efficiency of the metaconductor-based WPT system. Fig. 4 shows the fabricated metaconductor-based WPT system and measurement setup.

It is observed that the metaconductor-based WPT system exhibits ~11.5 dB improvement in S21 compared with solid Cu based counterparts.

IV. Conclusion

In this project, the Cu/Co MC-based WPT system is designed, fabricated, and characterized. The transmission coefficient and transfer efficiencies of the Cu/Co MC-based WPT systems are measured and compared with the Cu-based WPT system. It is proved that the utilization of the Cu/Co MC and low-loss glass substrate decreases the conductor loss and substrate loss, thus increasing the gain of the antenna and transfer efficiency of the WPT system.

V. Career Plan and Fellowship Impact

This is a great honor to be one of the winners of the IEEE Microwave Theory and Technology Society (MTT-S) graduate fellowship award. This fellowship award has encouraged my confidence and motivation to keep pursuing my research, and it also has provided me an opportunity to attend the IMS 2022 and have close interactions with many colleagues in the field. As for my future career, I am planning to work for a research institute in South Korea, where I can contribute more to the microwave community.

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