

Compact Stacked Metamaterial for Robust and Efficient Dual-band Wireless Power Transfer System

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(積層型メタマテリアルを用いた小型化デュアルバンド無線電力伝送システムに関する研究)

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論 文 内 容 の 要 旨

With the popularization of portable devices, such as smartphones, smartwatches, healthcare monitoring devices, and so on, the charging method has been shifting from wired to wireless. Chapter 2 focuses on the development of the WPT system. The entire wireless power transfer (WPT) is expected to be compact enough to be embedded inside the devices. Moreover, to cater to the requirements of different devices, WPT should not only transfer power but also offer additional functionalities, such as exchanging information (battery status) and device data (i.e., health data). While a single-band system commonly uses backscattering to transfer power and data alternately, the information input disrupts the power transfer, potentially decreasing power transfer efficiency (PTE). Thus, a dual-band system is considered a better choice for this application.

Additionally, recent research has focused on utilizing metamaterials to enhance the PTE of near-field WPT systems. Chapter 3 begins by discussing the background and challenges of using metamaterials for dual-band WPT. When the permeability of the metamaterial is near zero, it acts as a perfect lens, focusing and strengthening the electromagnetic (EM) wave in the desired direction (from the transmitter (Tx) to the receiver (Rx)). The metamaterial's dimensions can be optimized to achieve near-zero permeability at the desired frequency. The shape of the metamaterial is constrained to one dimension (1D), where the unit cells of the conventional metamaterial are arranged horizontally. However, using this type of metamaterial, it was found that the conventional 1D metamaterial can only improve the PTE of one band. Therefore, when a 1D metamaterial is used in the middle of a dual-band WPT system, the improvement in PTE for the other band is limited and lower than that of the first band. Consequently, there is a need for a metamaterial that can simultaneously improve the PTE of both bands, presenting an exciting and novel topic for dual-band WPT designers.

Motivated by this, the research aims to enhance the efficiency and robustness of dual-band WPT. Multiple metamaterials using stacked topology are proposed to improve the efficiency, tolerance of lateral misalignment, and mutual interference (isolation) performance of the dual-band system. The emergence of stacked metamaterials opens up more possibilities for lattice combinations in metamaterials. Thus, in Chapter 4, a multi-mode metamaterial is proposed, comprising two stacked metamaterials (Type I and Type II) that are effective for both bands of the dual-band WPT system. These two metamaterials are horizontally aligned, considering cross-polarization. As a result, the newly proposed metamaterial exhibits characteristics of two

self-resonant frequencies (or two near-zero permeability points) that match the WPT working frequency. When the metamaterial is placed in the middle of the dual-band WPT system, it exhibits three modes: lower mode, higher mode (when Type I or II is right opposite to the Tx (Rx)), and balanced mode (when the center of the metamaterial is right opposite to the Tx (Rx)). In the best case, the proposed metamaterial can improve efficiency from 0.04 to 39%. However, the proposed metamaterial demonstrates inferior performance when the Tx and Rx are misaligned, resulting from the three modes.

To address this issue, Chapter 5 focuses on resolving the problem identified in the previous chapter. The proposed metamaterial involves alternately stacking two types of unit cells, with each unit cell effective for a specific band. Consequently, a unit cell of a hybrid split ring resonator (SRR) is proposed, exhibiting three self-resonance frequencies, allowing for three near-zero permeability points within the desired frequencies. Based on experimental results, the figures of merit (FOM) are 0.92 at 390 MHz and 0.85 at 770 MHz, with a power transfer distance of 20 mm. This represents a significant improvement compared to recently proposed dual-band WPT systems with metamaterials. Furthermore, due to the proposed metamaterial's topology, its size is reduced by 50% ($20\text{ mm} \times 20\text{ mm}$) compared to the multi-mode metamaterial ($20\text{ mm} \times 40\text{ mm}$). Additionally, the tolerance of lateral misalignment is significantly improved in comparison to the system without metamaterial and the system with the multi-mode metamaterial, making the entire system more robust in terms of transfer efficiency and lateral misalignment.

From the perspective of mutual interference (isolation) performance between the two signal bands, Chapter 6 introduces a metamaterial-inspired absorber for a recently proposed dual-band simultaneous information and power transfer (SWIPT) system. The proposed metamaterial acts as an absorber to mitigate interference between the signal and power bands when a signal is input into the signal port. A 10-mm-thick human body equivalent phantom is used for the SWIPT system's evaluation. Experimental results indicate that embedding this absorber between power and signal ports in both Tx and Rx of a SWIPT system results in a 3 dB improvement in isolation performance. Concurrently, with the assistance of the proposed absorber, the data rate improves by 3.6 Mb/s, allowing signals to be transmitted with 5 dBm weaker power than the original system.

In Chapter 7, a novel AI-based method is proposed to automatically optimize the DGS-based wireless power transfer (WPT) system within the desired working frequency. The method leverages a dual annealing algorithm to achieve fast system optimization.

Finally, in Chapter 8, the proposed metamaterials in this research and the problems to be addressed in future work are summarized. Future plans include utilizing machine learning techniques to rapidly and automatically optimize the metamaterial's dimensions and the WPT system based on DGS.