

Metamaterial-Enhanced Wireless Power Transfer for Implantable Medical Devices

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Neurostimulation technologies have significantly improved treatment outcomes for various disorders by efficiently managing and alleviating symptoms. The effectiveness of these devices depends on a consistent and reliable power supply. Currently, most systems rely on batteries, facing limitations in device size, longevity, and operational reliability. Efficient wireless power transfer (WPT) systems are thus essential for the effective functioning of implantable medical devices. Traditional WPT systems, employing inductive resonant coupling, are often constrained by coil quality factors and mutual coupling, leading to limitations in alignment sensitivity and transmission distance. This study introduces a transformative approach by integrating dual-layer thin-film metamaterials into WPT systems, significantly enhancing power transfer efficiency and reliability for biomedical implantable devices. Metamaterials, engineered periodic materials with properties such as negative permeability and permittivity not found in nature, can control and enhance magnetic flux, thereby improving WPT efficiency and extending the transfer distance; crucial for the lower frequencies used in biomedical applications.

Building on our group's prior work on low-frequency metamaterials, such as ferrite-loaded solenoid unit cells (E. S. Gámez Rodríguez et al., "Compact low-frequency metamaterial design for wireless power transfer efficiency enhancement," *IEEE Trans. Microwave Theory Tech.*, vol. 64, no. 5, 2016), this research focuses on miniaturizing the setup into a compact, thin structure that can be integrated into wearable systems while maintaining previous functionalities. Our design features a 3×3 array of dual-layer square spiral resonators. Each unit cell is designed to confine the magnetic field between an external transmitter and a small, implanted receiver. Operating within the lower frequency ISM band, our system is finely tuned to a frequency that balances effective wireless power transmission with adherence to international safety standards. Simulations conducted through CST Studio Suite provide detailed insights into electromagnetic field behaviors, validating the effectiveness of the dual-layer thin metamaterial in enhancing system performance under various operational conditions. Experimental validation confirmed computational findings, demonstrating marked improvements in efficiency and reliability over traditional systems, particularly in scenarios involving non-ideal alignments—a frequent challenge in clinical settings. Both simulation and experimental data validate that the introduction of precisely controlled thin metamaterials leads to systems with much higher transmission efficiency and robustness to a great extent of misalignment between transmitter and receiver.

This research demonstrates the technical feasibility and safety of compact metamaterial slabs in enhancing wireless power transfer systems and introduces a paradigm shift in the powering mechanisms of implantable medical technologies. This advancement is anticipated to reduce the need for surgical battery replacements and enhance patient comfort, potentially revolutionizing the operational sustainability of implantable medical devices. The application of these advanced materials promises to extend device longevity and improve patient outcomes by offering a more reliable and efficient power supply.