A 13.56 MHZ METAMATERIAL VIA THE INCORPORATION OF POLYIMIDE BASED FPCB AND NIZN FERRITE FOR WIRELESS POWER TRANSMISSION ENHANCEMENT

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ABSTRACT

In this paper, a miniaturized flexible metamaterial made of five-layered flexible print circuit boards (FPCB) with the incorporation of NiZn ferrite strips is proposed to effectively enhance the wireless power transmission efficiency (PTE) of the implantable biomedical devices. The proposed approach achieves a 94% size reduction, i.e., only 1/16 of the previous metamaterial design and exhibits better PTE enhancement over longer distances and under misalignments. The innovation lies in employing an equivalent *LC* model for metamaterial design, streamlining the design process, and leveraging advanced fabrication technologies for miniaturization. Experimental results demonstrate that the PTE of the coil antenna system can be significantly enhanced by incorporating the metamaterial when the transmitting and receiving antennas are well-aligned and spaced at least 1 cm apart. Specifically, when the coils are aligned with 1.5cm and 2 cm spacing, the transmission efficiency increases from 38.2% to 46.7% and from 19% to 30.2%, respectively. Moreover, with a coil separation of 3cm, the transmission efficiency doubles from 4.1% to 9.3%, indicating a notable enhancement in power efficiency. Due to its unique characteristics, including a compact form factor, lightweight design, and exceptional power enhancement, the flexible metamaterial holds promising potential for future applications in wireless charging technology, particularly for implantable medical devices.

KEYWORDS

Metamaterial, Flexible Printed Circuit Board, Wireless Power transmission, Implantable Biomedical Device, Neural Stimulator.

INTRODUCTION

Metamaterials are synthetic materials engineered to possess extraordinary properties not found in nature. They can manipulate the path of electromagnetic waves as they propagate through them. In 2000, D. R. Smith's team pioneered the creation of the first metamaterial with negative permittivity and negative permeability at microwave frequencies using metal split rings as unit cells, thus demonstrating negative refraction in the microwave spectrum.[1] These remarkable properties arise from the intricate geometric structures and precise dimensions of metamaterials. Throughout the early twenty-first century, metamaterials garnered substantial interest and research attention from scientists worldwide. These materials deviate from the behaviors of conventional materials by exhibiting negative permittivity and/or negative permeability, enabling functionalities such as electromagnetic wave focusing. Metamaterials, owing to their composite composition, challenge conventional electromagnetic principles. A variety of metamaterial structures have been developed and extensively utilized in applications including microstrip antennas, filters, magnetic resonance imaging (MRI)[2], and wireless transmission via magnetic coupling resonance. [3]

In recent decades, many research teams have explored the application of metamaterials in wireless transmission devices and discovered that they can used for enhancing the transmission efficiency of wireless charging. [4] By modifying the structure size, shape, and material of each unit cell, the working frequency of metamaterials can be controlled. In previous studies, metamaterials operating at a frequency of 13.56MHz had excessively large dimensions, rendering them impractical for use in personal portable devices. [5-8] Therefore, this research utilizes flexible printed circuit boards (FPC) to increase the capacitance of metamaterials, thereby reducing their size at the same operating frequency. Through further miniaturization, the goal is to apply them practically in portable electronic instruments and devices, enhancing wireless charging efficiency. Metamaterials tailored to operate at a frequency of 13.56MHz are fabricated to address the issue of low power transmission efficiency (PTE) in wireless charging when the antenna cannot be properly aligned or when the distance is too far.

In the past, most implantable medical devices required battery replacement to meet power demands. However, frequent battery replacements are not only time-consuming but may also risk infection during the process. In recent years, to meet growing medical needs and achieve better medical quality, implantable medical devices have gradually attempted to use wireless charging for power supply. This method addresses the problem of short battery life due to the small size of medical equipment. Experimental results have not only increased utilization but also extended the lifespan of the equipment. Various miniaturized implantable techniques and simulation and testing methods, such as antenna types and designs, [6] antenna sizes and operating frequency bands, [7] human safety considerations, design environments, and testing methods, must be rigorously considered. Additionally, in practical operation, implanted antennas may be affected by other biomedical sensors or circuit components, thereby affecting the performance of the implanted antennas. Therefore, in the context of wirelessly charging implantable medical devices, antenna size, power consumption, radiation rate, transmission distance, etc., are all important design considerations. [8]

In terms of commercial applications, varieties of wireless charging medical devices have already been introduced. [9] One of major applications focuses on the wireless charging device for deep brain stimulation (DBS) used to treat Parkinson's disease patients. The most prominent symptoms of Parkinson's disease include uncontrollable movements, such as tremors, stiffness, difficulty with balance and coordination, Patients may also suffer walking, speaking, memorizing, as well as sleeping, problems deteriorating over time. For Parkinson's disease patients who do not respond well to medication, Doctors may recommend deep brain stimulation surgery for the patients. [10] To perform electrical stimulation therapy, such a medical device utilizes two coils for wireless charging and signal transmission to the device implanted in Parkinson's disease patients.

During the surgical procedure, electrodes are implanted into specific areas of the brain and connected to small devices implanted in the chest. [10] These devices and electrodes stimulate specific areas of the brain that control movement without causing pain. When abnormal electrical signals occur in the brain of Parkinson's disease patients, the implanted stimulator generates opposite electrical signals that reach the brain through wires, [11] helping to alleviate many movement-related symptoms of Parkinson's disease. Thus, while the position of the wireless charger deviates slightly, alignment issues arise between the transmission and reception ends. Incomplete alignment of the wireless charging antenna reduces charging efficiency and increases power consumption. Additionally,

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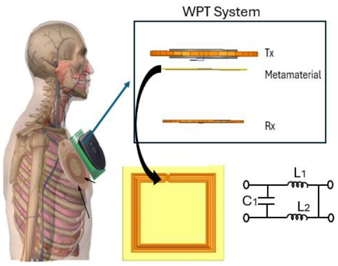


Figure 1: The scheme of wireless charge system with metamaterials and neurostimulator.[5]

since implanted stimulators and wireless chargers may not be on the same plane due to various factors, charging may occur at an angle, reducing charging efficiency. Therefore, our laboratory previously proposed using metamaterials to resolve these issues.[5] Its application is illustrated in Figure 1, where metamaterials are placed between the transmission and reception ends of the antenna to enhance the transmission efficiency of wireless charging. Nevertheless, such a 13.56MHz metamaterial for near-field WPT in implantable medical devices is bulk, i.e. 8.5 x 8.5 cm^2, for each unit cell, limited practical applications for portable wireless charging. In this paper, we propose a miniaturized flexible metamaterial, employing flexible print circuit boards (FPCB) technology and the incorporation of NiZn Ferrite strips to effectively enhance the wireless power transmission efficiency (PTE) of the implantable biomedical devices.

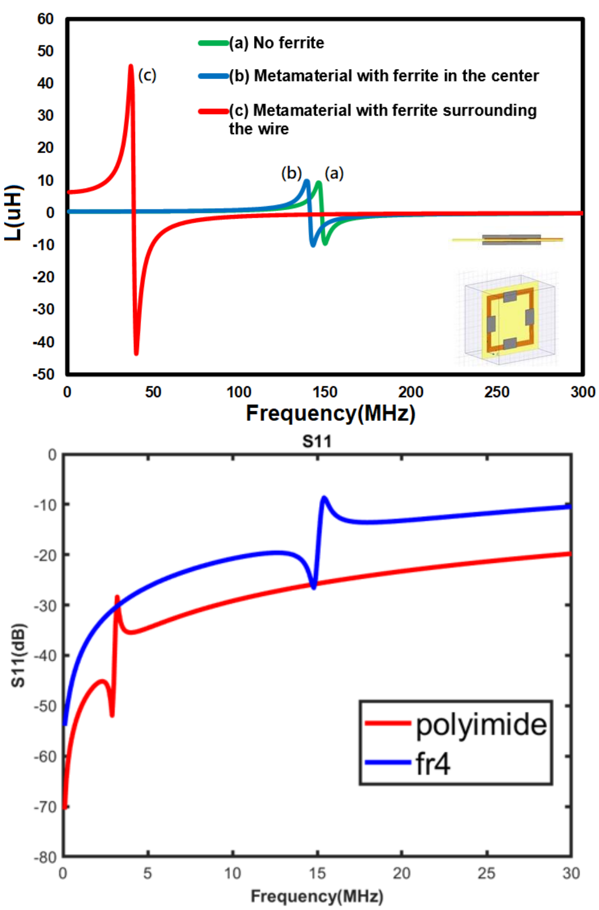


Figure 2: (a) Simulated inductance values of the coil inductors with/ without soft ferrites. (b) Frequency shift by using polyimide(red) to replace FR-4(blue)

Figure 3: The measured PTE spectrum of Tx and Rx coil antennas with/without metamaterial.

METAMATERIAL DESIGN AND EXPERIMENT SETUP

In this study, we adopt the design proposed by Wang et al. [12], which entails a 3D arrangement of double-side square spiral structures. The metamaterial is constructed with *LC* unit cells featuring a five-layered configuration of Cu wire and polyimide substrate, with magnetic strips positioned along the edges of the unit cell to enhance both inductance and capacitance. To determine the resonance frequency of the metamaterial, Ansys HFSS simulation software is employed to simulate its S parameter-frequency diagram. The simulation results (Figure 2(a)) demonstrate the effectiveness of utilizing the deployment of patched ferrites, i.e., NiZn as shown in the inset, to enhance inductance and a thin layer of polyimide with a thickness of 32.5μm instead of FR-4 material (Figure 2(b)) to increase capacitance. These enhancements facilitate the design of a metamaterial resonating at 13.56 MHz and the enhancement of PTE, as depicted in the PTE spectrum of two antennas with and without the metamaterials in between (Figure 3). Furthermore, the newly fabricated flexible metamaterial, comprising a 3 by 3 array, remains smaller in size compared to a unit cell of the previous design (Figure 4(a)).

The measured PTE of two antenna coils with the flexible metamaterial in between is calculated using the formula:

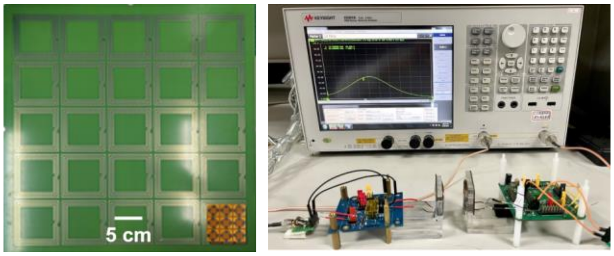
$$Efficiency(\%) = \frac{P_R}{P_T} \times 100\%$$

$$= \frac{I_R V_R}{I_T V_T} \times 100\%; \quad R{:}\,Recevier\ coil,\ T{:}\,Transmitter\ coil$$

For PTE measurement, a Keysight E5061B instrument is utilized under various conditions. Figure 4(b) illustrates the setup of the experimental apparatus, where 160 pF capacitors are connected in parallel with the transmitting coil antenna, and a 130 pF capacitor is connected in series with the receiving coil to mitigate antenna parasitic losses.

RESULTS AND DISCUSSION

Firstly, we examine the impact of inserting metamaterial between two well-aligned antenna coils, namely the T_x and R_x coils. Figure 5 displays the measured PTE of these coils at varying separations before the insertion of the metamaterial. The separation between the coils is denoted as D, as depicted in the inset of Figure 5. The findings validate the effectiveness of the metamaterial design, exhibiting maximum PTE at 13.56 MHz. Furthermore, the results indicate that PTE increases as the separation distance, D, decreases. Specifically, when D is set to 1 cm, the PTE can reach up to 60%, attributed to reduced flux leakage between the coils. Following the same configuration with two well-aligned coil antennas, the PTE enhancement with the incorporation of the metamaterial can be



(a) (b)

Figure 4: (a) As-fabricated metamaterial with the previous metamaterial design and (b) The setup of the experimental apparatus.

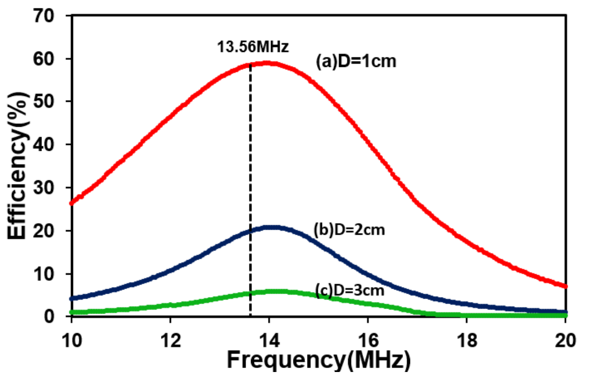


Figure 5: The measured PTE spectra of two antenna coils, i.e. Tx and Rx coils, with different separations. The inset shows these two antenna coils.

accomplished, while the D value is larger than 1 cm as shown in Figure 6. For the cases of the coil antennas separated by 2 cm and 3 cm, the PTE can be improved from 19% to 30.2% and 4.1% to 9.3%, respectively, achieving at least 1.6X efficiency enhancement.

Various application scenarios were tested to validate the effectiveness of enhancing PTE through miniaturized metamaterial usage. In a setup with two misaligned coils, featuring a 1 cm horizontal offset as depicted in Figure 7, PTE enhancement was observed upon inserting the metamaterial. When the separation between the misaligned coils was 1.5 cm, PTE decreased from 51% to 20%, but with the inclusion of metamaterial, it increased to 30%. In configurations with axial offset, illustrated in Figure 8, metamaterial consistently improved PTE. Specifically, for 20° and 50° axial offsets, PTE increased from 27.1% to 38.8% and from 3.4% to 7.7%, respectively, upon metamaterial insertion. These experimental outcomes confirm the efficacy of our proposed approach, showcasing a notable PTE increase, comparable to our previous design, affirming the miniaturized metamaterial's cap

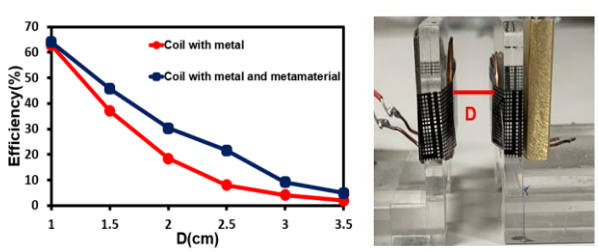


Figure 6: The PTE measurement results decreasing with the spacing between two well aligned antennas with and without the incorporation of the miniaturized metamaterial.

ability in enhancing performance.

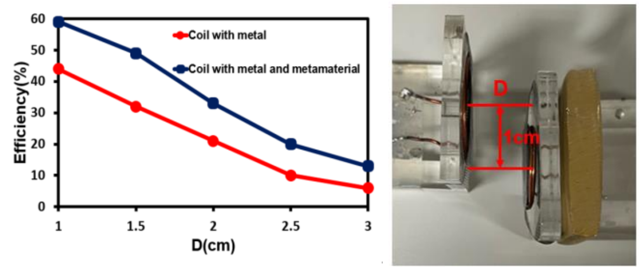


Figure 7: The PTE measurement results decreasing with the spacing between two antennas with horizontal misalignment of 1cm offset with and without the incorporation of the miniaturized metamaterial.

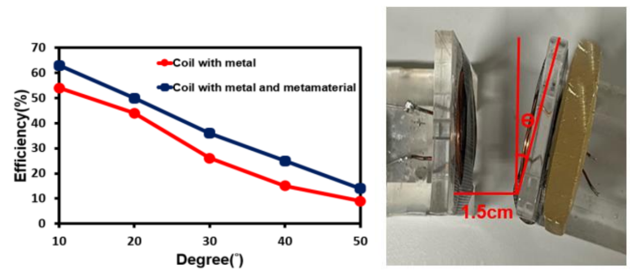
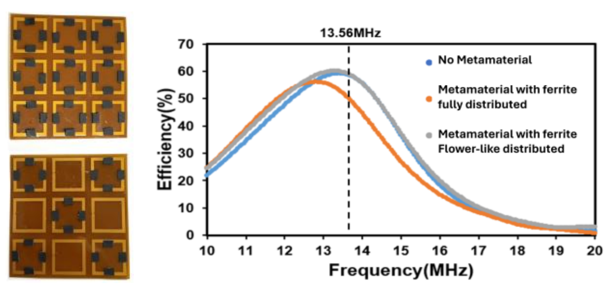


Figure 8: The PTE measurement results decreasing with the axial offset angle θ with and without the incorporation of the miniaturized metamaterial.

Figure 9 compares PTE across different ferrite distributions, highlighting the effectiveness of our proposed scheme in addressing frequency drift concerns. Notably, the flower-like ferrite distribution stands out for its ability to counteract potential PTE decay. This advantageous distribution minimizes mutual interference among neighboring magnetic materials, as their induced magnetic field directions differ and effectively cancel each other out. Thus, adjusting them to a flower-like magnetization pattern reduces interference, improving resonance frequency stability and PTE reduction. It is noted that the maximum PTE values for well-aligned antenna coils with a 1 cm separation remain consistent between scenarios without metamaterial insertion and the incorporation of the flower-like distribution design. This suggests that any energy loss from the metamaterial's metal, dielectric, and magnetic properties during power transmission has been compensated by the transmission gain from the material, resulting in similar PTE values. Further optimization efforts are underway in the new design, including adjustments to the unit cell size and material properties. For instance, introducing low-loss materials or materials with higher permeability and permittivity is being explored.



(a) (b)

Figure 9: (a) The ferrite distribution on the metamaterials: fully distributed(up) and flower-liked distributed(down) (b) The measured PTE spectrum of the metamaterial placed in between Tx and Rx coil antennas.

Table 1: The characteristic comparison of the developed metamaterials.

	Chen et al. [5]	Shaw et al. [13]	Khuyen et al. [14]	Bilotti er al. [15]	This work
Unit Cell Size	85 mm (~λ/261) (coupling loop)	24 mm (~λ/5)	62.5 mm (~λ/12)	λ/65~λ/250 (Multiple spilt rings/spiral rings)	20 mm (~λ/1106) (coupling loop)
Operational Frequency	13.56 MHz	2.45 GHz	400 MHz	>1GHz	13.56 MHz
Metal /Substrate	Cu/FR-4	Cu/FR-4	Cu/FR-4	Cu/FR-4	Cu/FPCB
Working Distance	1.5 cm	6~12 cm	200 cm	N/A	1.5 cm
PTE Enhancement (without/with metamaterials)	46% / 51% (Cu back, 1 cm misalignment) 39% / 46% (Cu back, 15° axial offset)	13.24% / 22.86% (Pork slab back) 10.30% / 19.91% (Human hand back)	N/A	Simulated Q/Q_{SRR} : 6/3 (10 turns copper / 5 turns copper) ※Q_{SRR}: The quality factor of regular SRR	45% / 58% (Cu back, 1 cm misalignment) 27.1% /38.8 % (Cu back, 20° axial offset)

Table 1 lists a comparison of prior metamaterials indicating this newly proposed structure can exhibit not only the functions in the magnetic field strength enhancement but also the largest size reduction with respect to the corresponding operational frequency regime [5, 13-15]. Although Bilotti et al. had proposed to reduce the size of metamaterials by increasing the number of split rings or spiral turns, no experimental data was provided to validate the concept and practical applications of the miniaturized metamaterials.

CONCLUSION

We have successfully demonstrated a flexible metamaterial at resonant frequency 13.56MHz. Comparing to the previous design, the length of the metamaterial has been reduced from 6.5 cm to 2 cm via a five-layered configuration of Cu wire and polyimide substrate incorporated with magnetic strips along the edges of the unit cell to enhance both inductance and capacitance. Various application scenarios including antenna spacing variance and antenna misalignment resulting from horizontal offset and inclination have been tested to validate the effectiveness of enhancing PTE through the miniaturized metamaterial usage. Experimental results show the maximum PTE values remain consistent between the newly design and the prior one indicating the miniaturization scheme is workable and makes the new design a promising candidate for practical applications in wireless power transmission for biomedical applications.

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