# A 13.56 MHZ METAMATERIAL FOR THE WIRELESS POWER TRANSMISSION ENHANCEMENT IN IMPLANTABLE BIOMEDICAL DEVICES

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## ABSTRACT

This paper presents a 13.56MHz metamaterial for wireless power transmission (WPT) enhancement in implantable biomedical devices based on the evanescent wave coupling mechanism. The power transmission efficiency (PTE) will increase from 46 to 51% with the metamaterial while the transmitting and receiving antennas are placed with a 1 cm distance and 1cm offset horizontal misalignment, will increase from 39 to 46% with the metamaterial while the two antenna planes are placed at a distance of 1.5 cm with an axial offset of 15°, and will increase from 28 to 50% with two pieces of metamaterial placed with a 0.5cm distance while the two antenna planes are placed with a 1.5 cm distance and 1 cm offset horizontal misalignment.

## KEYWORDS

Metamaterials, Power Transmission Efficiency (PTE), Wireless Power Transmission, Implantable Biomedical Device, Neural Stimulator.

## INTRODUCTION

With the advancement of semiconductor technology, the global bioelectronic market could grow at a CAGR of 11.6% during the period 2017-2025 resulting from a high demand in implantable medical devices ranging from cardiac pacemakers used to replace a defective natural cardiac pacemaker, bioelectronics ears used to provide cochlear prostheses to a person with hearing impairment, artificial retina used to restore eyesight to the blind, to neural recorders and stimulators used to treat patients with Parkinson's disease and epilepsy, etc. [1-4] Such implantable medical devices are branching out to new types of therapies such as spinal cord stimulators, sacral nerve stimulators, and vagus nerve stimulators for pain management, urinary urge incontinence and treatment of traumatic brain injury applications, respectively [5-7].

Present technology development of the implantable devices mainly focuses on how to accomplish the characteristics of smaller form factor, lower weight and cost, more functions, longer battery lifetime and reliability [8]. For example, the deep brain stimulator for Parkinson's disease treatment requires to be implanted inside human brain for sensing and stimulating the neural signal [9]. The patient must undergo surgery, which will cause unnecessary inconvenience and safety concern to the patient for battery replacement in the stimulation system. As a result, these implantable medical devices should be equipped with either a long-term reliable power supply or an alternative power source. For preventing the inevitable surgery due to the battery replacement, wireless charging technology based on inductive coupling mechanism has been developed and applied for the devices in recent years [10]. Meanwhile, according to the Food and Drug Administration (FDA) regulations, implantable medical devices are subjects to a series of examinations regarding biocompatibility and manufacturing processes. Manufacturers generally utilize bio-degradable materials for implantable medical devices. If the scenario can be applied with the materials, metal packaging, such as titanium case, is generally designated for the protection of non-biocompatible electronic systems for implant purpose [11]. Fig. 1 shows the scheme of deep brain stimulation for Parkinson's disease. A pacemaker-like device, neurostimulator, with wireless charging system is surgically implanted beneath the collarbone about 1cm from skin and charged by a patch. Since the near-field coupling efficiency in an implantable wireless power transmission (WPT) system decreases with the distance, misalignment between the transmitter and the receiver antennas in the body, and eddy current loss resulting from the metal packaging, a poor wireless charging efficiency has been a predicament in the deployment of the charging scheme.

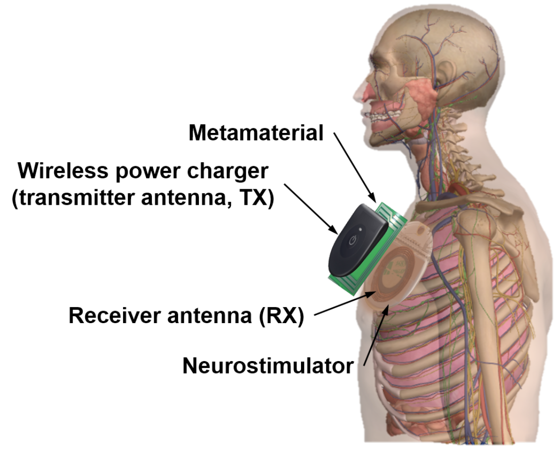


*Figure 1: The scheme of a deep brain stimulation system for Parkinson's disease.*

13.56 MHz in the ISM band has been one of the most commonly used carrier frequency for medical applications owing to less energy absorption and minimal tissue damage resulting from body penetration. Prior researchers have shown metamaterials could be used for improving WPT by enhancing evanescent waves [12-15]. In this paper, a metamaterial designed with a resonant frequency of 13.56 MHz has been demonstrated for improving the WPT efficiency of the implantable biomedical devices with misaligned wireless charging antennas on a metal plate for the first time.

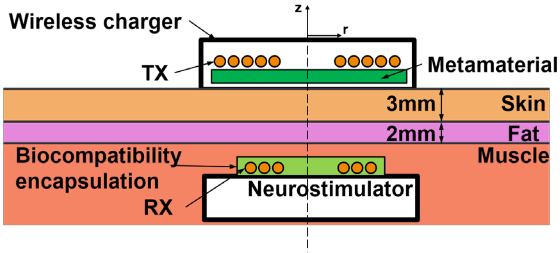


*Figure 2: 2-D axially symmetrical configuration of the wireless charger system and neurostimulator with the incoporation of the proposed metamaterial.*

## METAMATERIAL DEISGN AND EXPERIMENTAL SETUP

Since Pendry theoretically proposed the negative index of refraction material concept enabling subwavelength focusing effect, arrays of split-ring resonators (SRRs)-based metamaterials have been widely designed, realized, and characterized for varieties of applications including frequency tuning, antenna radiation, and biosensing, etc. [16-18] Basically, the negative permeability and permittivity characteristics of metamaterials can facilitate the amplitude enhancement of an electromagnetic wave propagating through it. As a result, Fig. 2 conceptualizes the utilization of the proposed 13.56 MHz metamaterial for implantable biomedical devices. Due to bio-packaging complexity concern, the metamaterial is placed between the transmitter and receiver and close to the transmitter, i.e. outside the body.

In this work, we basically follow the design, which is a 3D arrangement of double-side square spiral structures proposed by Wang et al. [15] The proposed metamaterial comprises *LC* unit cells made of three layers of copper and FR-4 as shown in Fig. 3. The middle layer is FR-4 substrate. The top and bottom layers are three-turn clockwise leading wires connected with each other through the FR-4 layer. The leading wire layers contribute the inductance, $L_1$ and $L_2$, while FR-4 layer contributes the capacitance, $C_1$ as shown in Fig. 3(b) where the designated total inductance and capacitance are ~4.58 μH and 44.4 pF, respectively.

For validating the effectiveness of the metamaterial on WPT enhancement, the vector network analyzer Keysight E5061B is utilized to measure the efficiency of coil antennas under different conditions where two 820 pF multilayer ceramic capacitors are connected with the transmitting coil antenna in parallel and a 270 pF multi-layer ceramic capacitor is connected in series with the receiving coil for the elimination of antenna parasitic loss. The measured *S* parameters are converted to *Z* parameters for the calculation of antenna coupling efficiency as follows,

$$PTE = \frac{|Z_{21}|^2}{R_L |Z_{11}|} \quad (1)$$

where $Z_{ij}$: the entry of row and column of the two-port model of the system impedance matrix and $R_L$: the load resistance. The highest measured PTE between the antenna coils is about 60.8% while the two antenna planes are placed with a distance of 1 cm. Fig. 3(e) shows the measured PTE spectrum of the two coil antennas with the metamaterial in between. A lower resonant frequency, i.e. 12.3 MHz, is resulting from the introduction of the parasitic effect between the metamaterial and antennas. The spectrum peak happening at a lower frequency, i.e. ~12 MHz, is resulting from the mutual inductance increase between the metamaterial and antenna coils.

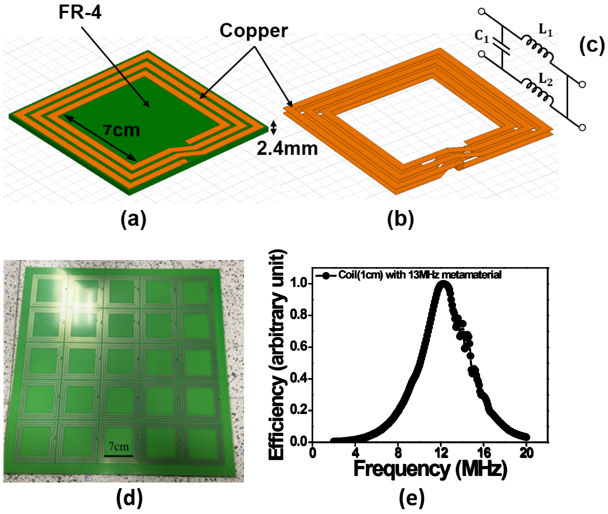


*Figure 3: (a)The proposed unit cell of the metamaterial structure, (b)equivalent LC circuit of each metamaterial unit cell without FR-4, (c) the as-fabricated metamaterial for wireless power transmission enhancement, and (d) the measured spectrum of the metamaterial placed in between Tx and Rx antennas.*

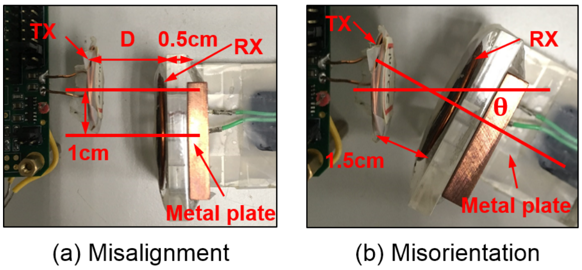


*Figure 4: The placement of transmitter and receiver antenna with a metal backplate for mimicking the environment of the wireless charging: the scheme with (a) horizontal misalgnment and (b) axial offset.*

## RESULTS AND DISCUSSION

For mimicking the environment of wireless charging usually accompanied with metal packaging for an implantable biomedical device, the PTE will be measured for validating the effectiveness of the metamaterial under the circumstances where the receiver antenna with a 0.5 cm thick Cu back plate will be placed with a 1cm offset horizontally misalignment or axial offset angle $\theta$ with respect to the transmitter one as shown in Fig. 4. Because the incorporation of the Cu plate will result in the effective reluctance increase of the receiving coil, which will cause the increase of the overall system resonant frequency, we design and fabricated another metamaterial coupled with the coil antennas to exhibit a spectrum peak at a higher frequency, i.e. 13.34 MHz, for the evaluation of increase from 28% to 50% with two pieces of metamaterial, placed with a 0.5 cm distance, while the two antenna planes are placed with a 1.5 cm distance and 1cm offset horizontal misalignment as shown in Fig. 7.

Want et al. has pointed out the enhancement in the magnetic resonant coupling system is essentially resulting from evanescent wave coupling mechanism, which can make the virtual distance between two resonators so smaller [15]. Fig. 7 further verifies this concept. The incorporation of two pieces of metamaterials in the antenna coils with a distance of 1.5 cm can enhance the PTE as good as the one only with a 1cm coil antenna distance. Nevertheless, how the metamaterial can enhance the case of the misaligned coil antennas even with axial offset still requires further investigation.

For the sake of clinical practice, the metamaterials must be deployed close to the transmitter antenna outside patient's body as shown in Fig. 2. Although adding more pieces of metamaterials could improve the antenna misalignment efficiency, it also results in the distance increase between two coil antennas and then PTE reduction. Meanwhile, the overall size of the metamaterial is about 40 $cm^2$, which is also too big to be practical for the application in the proposed wireless charging scheme. According to the theory derived by Popa et al., the amplitude enhancement of the evanescent wave will be independent of the thickness of the metamaterial [14]. Thus, miniaturization of the metamaterial becomes necessary.

The miniaturization can be further resolved via the incorporation of high $k$ and $\mu$ materials in terms of the shrinkage of material area and thickness, whereas the loss and dispersion of the metamaterials need to be accounted for low insertion loss. For the amplitude enhancement of evanescent wave in the metamaterial, the factors to determine the amplification are the magnitude permeability and permittivity of the materials including their complex parts that will results in the propagation loss [13,14]. In our case, since there is no magnetic material is introduced in the structure, the PTE can be further improved using Roger board instead of FR-4 substrate even in the MHz regime application due to the low dielectric loss. Once the incorporation high permeable magnetic materials for the inductance enhancement, low magnetic loss still needs to be considered. Besides, although the unit cell geometry of the metamaterials has been designed in the subwavelength regime, i.e. $<<\lambda$, further investigation is still requires regarding the possible loss of the EM field distributing in a small form and the geometry optimization for the best performance.

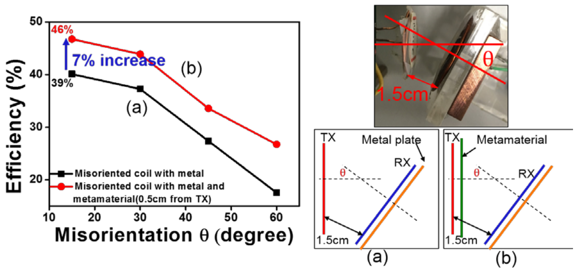


*Figure 5: The measurement results of antenna efficiency decreasing with the increase of axial offset angle θ betwee two antenna coils with (a) and without (b) the incoporation of the metamaterial.*

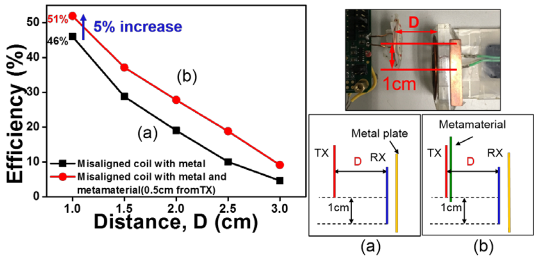


*Figure 6: The measurement results of antenna efficiency decreasing with the increase of the distance between two antenna coils with 1cm offset horizontally misalignment, (a) with and (b) without the incoporation of the metamaterial.*

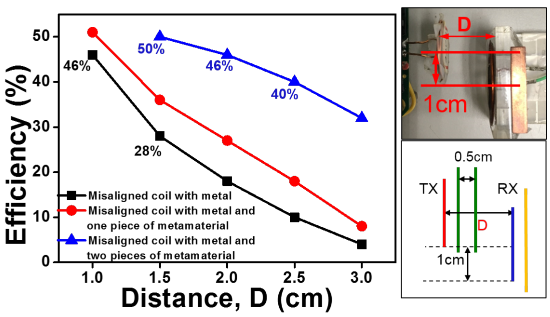


*Figure 7: The measurement results of antenna efficiency decreasing with the increase of the distance between two antennas with 1cm offset horizontally misalignment with and without the incoporation of two pieces of metamaterial separated by 0.5 cm.*

enhancement effectiveness where the unit cell size of the metamaterial is 5 cm instead.

Fig. 5 shows the measurement results indicating PTE will decrease from 58% to 39% but can be increased up to 46% with the metamaterial, while the two antenna planes are placed with a distance of 1cm and axial offset of 15°. Although the efficiency will decrease with the increase of axial offset angle, the results show the enhancement can be sustained for the offset with the angle up to 60°. Fig. 6 shows the antenna PTE will decrease from 58% to 46%, but can be increased up to 51% with the introduction of metamaterial when the two antennas are placed with a 1cm distance and 1cm offset horizontally misalignment. Similar enhancement effect can be also applied for the antenna coils with a larger distance. Furthermore, the PTE will

## CONCLUSION

We have successfully designed, fabricated and experimentally validated the efficacy of a 13.6MHz metamaterials for wireless power transmission enhancement in implantable biomedical devices. The metamaterial comprises 25 unit ells where each cell contains two layers of three-turn clockwise Cu wires connected and a middle layer of FR-4 substrate to form a resonant LC tank with a resonant frequency of 13.56MHz. The power transmission enhancement can effectively resolve the poor issues resulting from misalignment between the transmitter and the receiver antennas in the body and eddy current loss resulting from the metal packaging. A wireless power charging scheme for implantable device application is also proposed in this paper.

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