Metamaterial Antenna Design to Enhance Near Field Inductive Coupling for Biomedical Implants

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***Abstract*—This paper presents a concept for a double negative metamaterial (DNM)-based antenna to simultaneously enhance Wireless Power Transfer (WPT) and reduce Specific Absorption Rate (SAR) here for a network of distributed brain microimplants. The DNM copper coils are integrated in a FR-4 substrate, which has a dielectric constant of 4.3 and tangent loss (δ) of 0.025. Occupying a 2 $\times$ 2 cm^2 area, the DNM structure is introduced into our target wireless brain-machine interface (BMI) system operating at 915 MHz. Preliminary HFSS simulations show it provides 2 dB WPT enhancement and a 20% SAR reduction. We believe the work has the potential to address the WPT/ SAR co-optimization challenges for biomedical implants in general.**

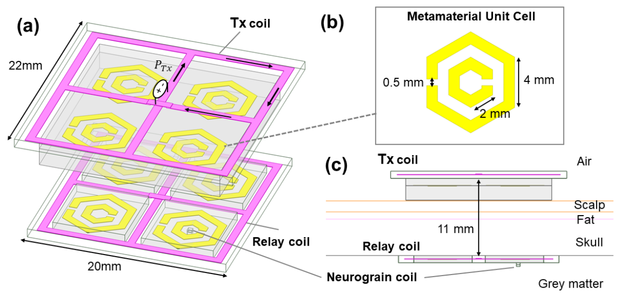

Fig. 1. (a) 3-layer inductively coupled "Neurograin" WPT system, (b) Proposed metamaterial unit cell, and (c) Cross-sectional view.

I. Introduction

Brain-machine interfaces (BMIs) have advanced considerably and translated into successful human clinical trials. Scaling these systems to support thousands of flexible, reconfigurable, and densely integrated neural nodes is one next research frontier. To that goal, sub-millimeter-sized wireless implants have been proposed [1-2]. Termed "Neurograins", these silicon chips integrate an on-chip coil for RF energy harvesting and up/ downlink wireless communication, as well as electrodes for single-channel neural recording/ stimulation.

The clinical viability for these implants hinges on delivering the required wireless power without violating the specific absorption rate (SAR) restrictions [3]. While research has explored SAR reduction for on-body applications [4-6], the implants' near-field inductively coupled wireless power transfer (WPT) system presents a different set of design challenges, and is relatively understudied [7-9].

This work proposes applying double negative metamaterial (DNM) structures in the inductive-coupled system of [1] to co-optimize WPT and SAR. Fig. 1(a) shows the trimetric view of the 3-layer system (highlighted in purple). Operating at 915 MHz, it is composed of: (i) a 'window-type' Tx coil external to the head, (ii) a 'window-type' relay coil implanted on the cortex, and (iii) a micro Rx-coil integrated on each Neurograin. Two metamaterial structures, each composed of copper coils (yellow) integrated in a FR4 substrate (gray), are placed under the Tx coil and within (on the same plane as) the relay coil, respectively. Fig. 1(b) provides the example design dimensions of the metamaterial element. Fig. 1(c) presents a cross-sectional view, displaying the relative vertical locations for the 3-layer coil system, the DNM structure and the brain tissues.

II. Metamaterial Design

Inspired by a split-ring resonator (SRR) architecture, the metamaterial structure of Fig. 1(b) incorporates hexagonal structures with integrated slots. A substrate-integrated technique is employed to achieve double-negative metamaterial properties. The side lengths of the inner and the outer rings are 2 mm and 4 mm, respectively. The slots have a gap of 0.5 mm. Fig. 2(a) illustrates the unit structure with the assigned floquet port, and Fig. 2(b) shows the substrate-enclosed structure, whch has a total 3 mm thickness. Fig. 2(c) depicts the 2 $\times$ 2 metamaterial array structure with overall dimensions of 20 mm $\times$ 20 mm. Fig. 2(d) presents the cross-sectional view. The 1 oz copper patch material is sandwiched between a 2 mm thick FR-4 superstrate and a 1 mm thick bottom substrate.

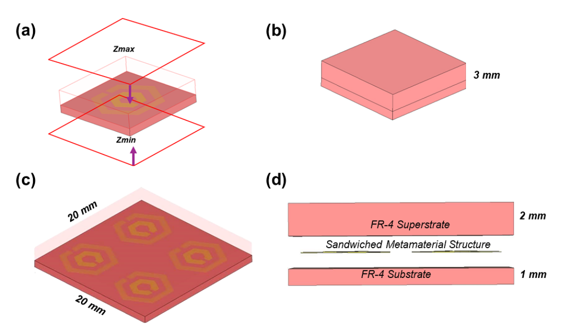

Fig. 2. The proposed metamaterial design: (a) Trimetric view with Floquet ports for the unit element, (b) Sandwiched unit structure, (c) Trimetric view of the complete metamaterial structure, and (d) Cross-sectional layer view.

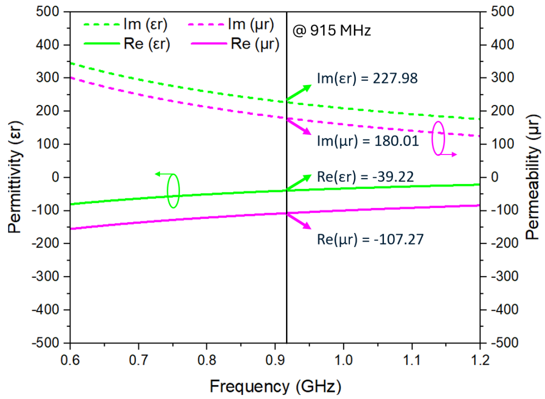

Fig. 3. Permittivity and permeability of the substrate integrated metamaterial versus frequency.

TABLE I
SAR AND S21 COMPARISON BETWEEN WPT SYSTEMS WITH/WITHOUT MATAMATERIALS

3-coil WPT system	***No Metamaterial***	***With Metamaterial***
S21 (dB)	-31.4	-29.4
P_{Tx} (dBm)	24	22
Peak SAR_{10g} (W/kg)	14.8	11.8

III. RESULTS AND DISCUSSION

A. Metamaterial Simulation and Discussion

To demonstrate the electromagnetic behavior of the designed metamaterial, the simulated permittivity and permeability results are shown in Fig. 3. The real part of the relative permittivity, Re(ϵ_r), is -39.22, while the imaginary part, Im(ϵ_r), is 227.98, indicating significant dielectric losses. Similarly, the real part of the relative permeability, Re(μ_r), is -107.27, and the imaginary part, Im(μ_r), is 180.01, reflecting substantial magnetic losses. These results confirm the metamaterial's left-handed behavior as characterized by negative permittivity and permeability, which limits the amount of electromagnetic energy dissipated on brain tissues at selected locations.

B. WPT/ SAR Simulation and Discussion

The metamaterial-enabled 3-coil Neurograin system of Fig. 1(a) is simulated in HFSS to extract the SAR performances. A Neurograin is placed at the most weakly-coupled spot to capture the worst-case WPT. The results are compared to that without the metamaterial structure. As shown in Table 1, the metamaterial enhances the WPT by 2 dB at the selected implant location, thus reducing the Tx power required from 24 dBm to 22 dBm. As a result, as presented in Fig. 4, the HFSS-simulated peak SAR substantially reduces by 20%, from 14.8 W/kg (observed in the area surrounding the intracranial relay coil) to 11.8 W/kg. While these initial results are encouraging, we are in the process of carefully analyzing the complex system, and re-optimizing the metamaterial structures/materials to enhance WPT efficiency and SAR for a large number of implants over a wider area.

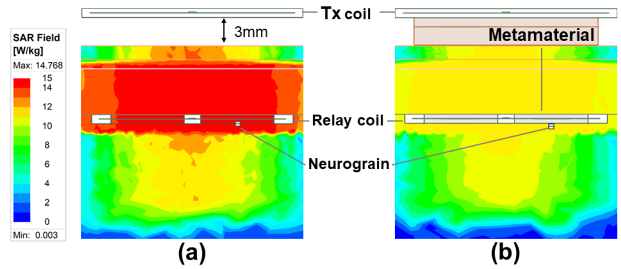

Fig. 4. HFSS-simulated SAR results (a) without metamaterial and (b) with metamaterial.

CONCLUSION

This study presents the preliminary design of double-negative metamaterial (DNM) to reduce the SAR for wirelessly-powered brain implant applications. HFSS simulations show that the metamaterial structure results in 2 dB increase in WPT efficiency and a 20% drop of SAR. Future work is needed to extend these results to cover a high number of microimplants distributed over a wider region.

ACKNOWLEDGMENT

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