Metamaterial-inspired Radio-frequency Coil Design for Ultra-high Field MRI

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***Abstract*—This report provides a brief summary of the main outcomes of the research project supported in part by the 2017 IEEE MTT-S Graduate Fellowship for Medical Applications. The research objective of the study is to improve the radio-frequency (RF) coil system used for transmission and/or reception of the magnetic resonance imaging (MRI) signal by using metamaterial-inspired coil designs. Specifically, this report will summarize the progress made regarding the originally proposed project and the new ideas resulted from it.**

I. PROJECT INTRODUCTION

One of the challenging problems of ultra-high field (UHF) magnetic resonance imaging (MRI) is creating highly efficient radio-frequency (RF) transmit/receive coils. My research work is focusing on the developing of new strategies to overcome the limitations of the commonly used RF systems and help to enable the potential benefits of the UHF MRI such as increased special and/or temporal resolution. The proposed approach is to use metamaterials (MM) and metamaterial-inspired coil designs to manipulate and improve the RF field distribution. The MM concept can be applied both in the development of novel coil design and as an addition to currently existing ones.

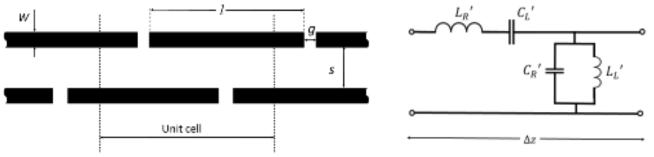
II. PROJECT OUTCOME

The first part of this project was to create a novel coil design based on the extended transmission line (TL) theory. A double-loop coil was created that introduced additional distributed lumped elements as shown in Fig.1(a) and (b). The proposed modified transmission line was then folded to form a loop resulting in Fig.1(c). An array of eight elements was formed as shown in subfigure (d) and the resulting RF field distribution is shown in subfigure (e) and (f) for the case of a typical coil array (TEM coil) and the proposed one, respectively.

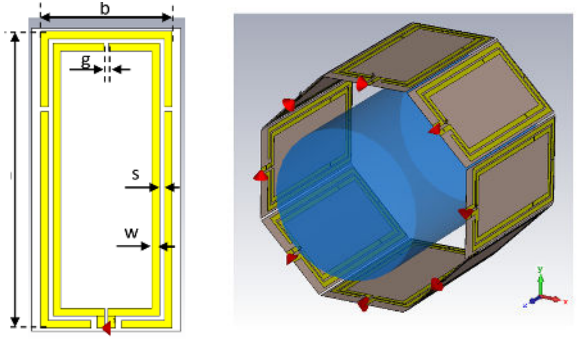
A. Double-loop RF coil

The results of this project were presented at the ISMRM2017 [1], the leading conference in the field of MRI. The proposed double-loop coil array was further tested at the 7T scanner. However, one challenging issue was immediately noticed during the measurements at the scanner. It is the coil sensitivity to the presence of the load and its position. The increased sensitivity arises from the fact that the distributed capacitance introduced by the gaps becomes very sensitive to the loading conditions. Unfortunately, after a series of experiments and discussions with the experts, it was concluded that in its current stage the proposed coil it not practical for the use at the MRI scanner as it requires a wide range tuning depending on the loading settings. Nevertheless, it was a good learning experience and it equipped me with a better understanding of the limitations and challenges of metamaterial application for MRI.

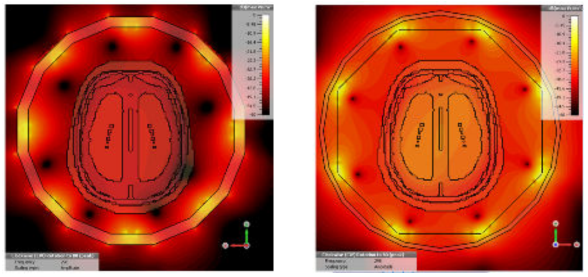
After this, a new project was started that employs the concept of a space-filling curve for the miniaturization of metamasurface field enhancer for UHF MRI.



(a) Proposed TL (b) Extended TL circuit



(c) Double loop (d) Proposed coil array model

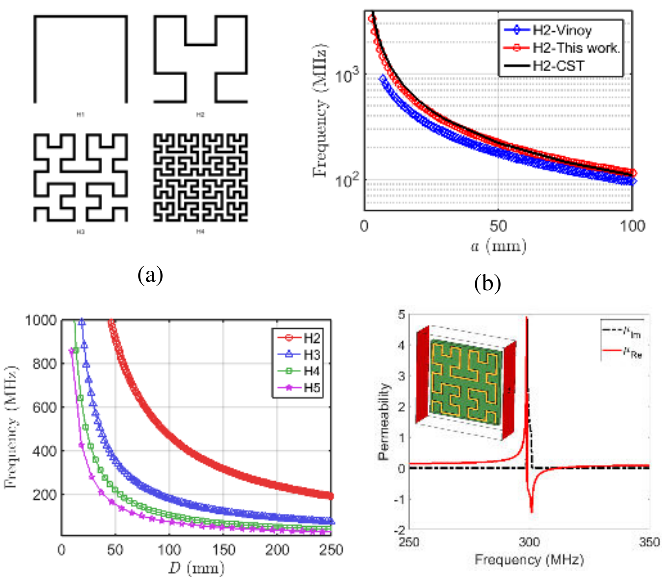


(e) B_1^+-field (TEM coil) (f) B_1^+-field (proposed coil)

Fig. 1: Double-loop coil simulation model and results.

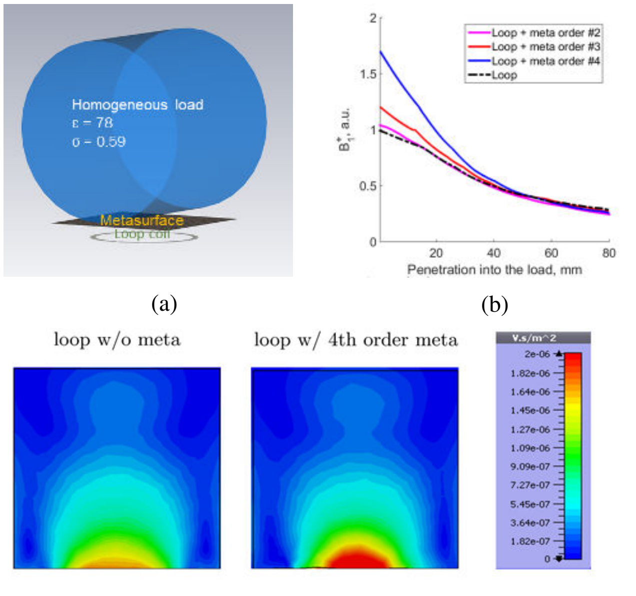
B. Hilbert curve metasurface

Many research groups are trying to make a MM or metasurface (MS) to manipulate and improve RF field propagation of the MRI coils [2], [3], [4]. However, one of the main limitations of any MM/MS field enhancer is its physical dimension, as the bore of the scanner has only a limited capacity. Keeping this problem in mind, we have proposed to use the concept of space-filling curves (SFC). A SFC is a mathematical concept used to describe a planar non-self-intersecting curve that fills up a certain area. When applied to the antenna field this means that a wavelength can be compactly ”folded” into a smaller area allowing to miniaturize resonators. Hilbert curve belongs to the family of space-filling curves and its first few orders are shown at Fig.2(a). Its intrinsic resonance frequency can be found e.g. using CST Microwave Studio Eigenmode solver. However, it can be time-consuming as the Hilbert curve order number increases and the geometry becomes more complex. To facilitate a fast resonance mode calculation a circuit model was proposed that describes the Hilbert curve resonance behavior accurately [5]. Fig.2(b) shows how the



(a) (b) (c) (d)

Fig. 2: (a) First four orders of Hilbert curve. (b) H2 resonance calculated using Vinoy et al. solution, the proposed solution, and CST. (c) Hilbert curve resonance behavior. (d) Hilbert curve H3 permeability near 300MHz.



(a) (b) (c)

Fig. 3: (a) Setup. (b) Field penetration inside the load. (c) 2D field distributions.

proposed circuit model can approximate the resonance of the Hilbert curve with respect to the width of the structure and compares it to those calculated using the earlier proposed solution by Vinoy et al. [6] and to that obtained using CST. The relative error of the proposed model is within 10%. Fig.2(c) shows the resonance behavior of the Hilbert curve of several orders calculated using the proposed circuit model. It can be seen that smaller resonators can be designed for the same frequency if the Hilbert curve order number is increasing. A MM with a negative refraction index discovered by Pendry [7] is able to focus electromagnetic field and provide sub-wavelength resolution. To observe this effect in a near-field application, such as MRI, only one of the material properties (ϵ or μ) needs to be negative [2]. Fig.2(d) demonstrates the MM behavior of the Hilbert curve around 300 MHz (operating frequency of a 7T scanner).

Hilbert curve was further integrated with a loop coil and placed in between the coil and the load, as shown in Fig.3(a). The RF field (B_1^+ field) penetration into the load is shown in Fig.3(b), where it can be observed that the field intensity improvement is stronger for the case of higher order Hilbert curve. Fig.3(c) shows the 2D RF field distributions inside the load for the case of with/without the proposed MS.

The results demonstrated here were published and presented at the ISMRM2018 [8]. Moreover, a more thorough analysis and experimental validation are summarized in the manuscript in preparation [5].

III. FELLOWSHIP IMPACT & CAREER PLANS

It has been a privilege to have my research work recognized by the IEEE Microwave Theory and Techniques Society (MTT-S). The reception of the award has not only motivated me tremendously for solving the challenging problems of MRI, but it has also improved my research work. Moreover, this recognition allowed me to attend the IMS-2017, where I got exposed to the latest developments in the microwave research and has a chance to network with the experts in the field. In the future I would like to join the industry and to solve real-life problems using the skill-set that I have developed during my PhD.

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I would like to thank my advisor Prof. Shao Ying Huang for encouraging me to apply for the MTT-S Fellowship and for her continuous help and support throughout the ups and downs of the research work. I would like to express my gratitude to Prof. Xiaotong Zhang for giving me the opportunity to work at the Zhejiang University 7T facility. Moreover, I am utterly thankful for all the fruitful discussions with Prof. Gregor Adriany.

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