Interdigitated Metasurfaces for Enabling Homogeneously Boosted Magnetic Fields during 1.5T MRI Scans

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***Abstract* — Metasurfaces, with their extraordinary ability to manipulate electromagnetic waves, are enabling a new and advanced phase of scanning in multiple medical diagnostic technologies. In recent years, metasurfaces have been showing promise in enhancing the scanning capabilities of one of the most promising clinical diagnostic techniques *i.e.* Magnetic Resonance Imaging (MRI). The signal-to-noise ratio (SNR) of an MRI scan is a measure of how clear and detailed the scanned image is. The higher the SNR, the clearer and more detailed scan images will be obtained which translates to a more accurate diagnosis of patient's medical conditions. Recently, researchers have shown that both rigid and flexible metasurfaces could improve MRI performance by enhancing SNR, with flexible metasurfaces better suited to MRI system adaptability. These reported flexible metasurfaces have shown a boost in SNR but have not claimed a uniform magnetic field enhancement throughout the phantom/human tissues. In this manuscript, we propose a new practical approach to uniformly boost SNR over the entire phantom using metasurfaces. The designed flexible interdigitated metasurface could provide a uniform enhancement of ~3 times in SNR over the entire phantom. This may be translated to a scan image from a ~3 times higher field strength MRI scanner than a typical 1.5T.**

Keywords* — *flexible interdigitated metamaterial,* 1.5T *MRI, signal-to-noise ratio, magnetic resonance imaging

I. Introduction

Metasurfaces are artificial materials designed to exhibit properties that are not found in nature and are created by manipulating their structure at the microscopic level [1]. The application of metasurfaces is rapidly advancing in the medical field, offering unique capabilities for surgical simulations, educational tools, patient care, and research programs. Metasurfaces, with their tailored properties, have the potential to transform various aspects of medicine and provide versatile solutions to challenges in diagnosis and treatment [1]. Magnetic Resonance Imaging (MRI) is a premier non-invasive diagnostic procedure that generates highly accurate images of the body's organs and tissues through the utilization of radio waves and magnetic fields. MRI uses nonionizing radiation, static magnetic fields, and electromagnetic energy to obtain detailed high-contrast images of soft and hard tissues for diagnostic purposes [1]. Signal-to-noise ratio (SNR) is a crucial component of MRI that affects the image quality and accuracy in diagnosis. SNR enhancements may result in better spatial resolution, measurement repeatability, and overall image quality [2]. A variety of techniques are still being used to push the limits of SNR optimization, which advances MRI as a diagnostic tool [2]. Among all these techniques, metasurfaces could provide a viable way to boost the SNR and enhance MRI system performance [2].

Metasurfaces can significantly increase the SNR by localizing and redistributing the RF magnetic field in the near-field region, leading to an improved image resolution and shorter scanning time [3]. However, getting a uniform enhancement throughout the phantom in different slices is still challenging with these reported metasurfaces as it boosts the SNR only in its proximity that decays with the distance from the metasurfaces.

In this paper, we report a flexible metasurface that focuses on uniform SNR enhancement over the entire phantom inside a birdcage scanner. The proposed metasurface has the ability to boost SNR at least thrice over different slices along the entire phantom, which could result in better probing of extremities and enhanced imaging by 1.5T MRI.

II. Design of the Proposed Metasurface

Fig. 1. depicts the proposed metasurface, featuring a top view and side view. The metasurface is a three-layered structure with the top and bottom layers made of copper with a thickness of 0.035 mm. The structure is a interdigitated structure (comb-like), separated by a distance (d_{sep}) of 0.25 mm, and each comb has a thickness (d_{st}) of 0.5 mm along all sides. The second layer is a Rogers RO4003C substrate with a dielectric constant of 2.55 and a thickness (t_{u}) of 0.8 mm and the distance (d_{s}) is 1 mm. The length of the unit cell (L_{u}) is 60 mm, with a unit cell dimension of 60 mm × 60 mm. The copper interdigitated structures are placed on the Rogers substrate on top and bottom, making the total thickness of the unit cell 0.87 mm (≤ 1 cm). The comb structures are not precisely aligned with one another. There exists a uniform gap of 0.2 times L_{u}, which is approximately 12 mm between their base and the adjacent strip. A cuboidal phantom, measuring 130 mm × 130 mm × 130 mm, containing

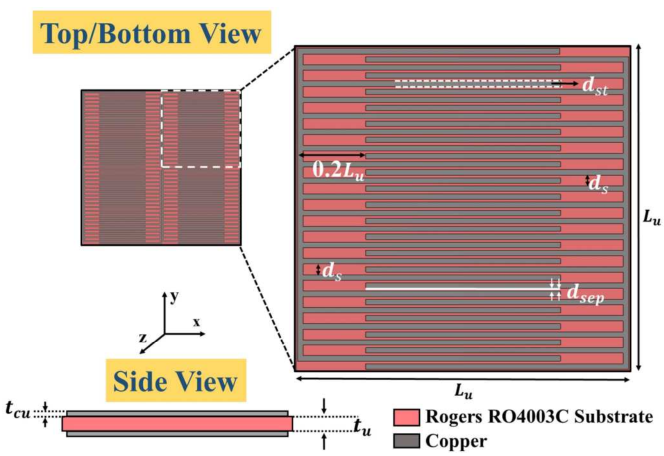

Fig. 1. Top/bottom and side view of the designed metasurface. The simulated metasurface is a 2 × 2 array of unit cell.

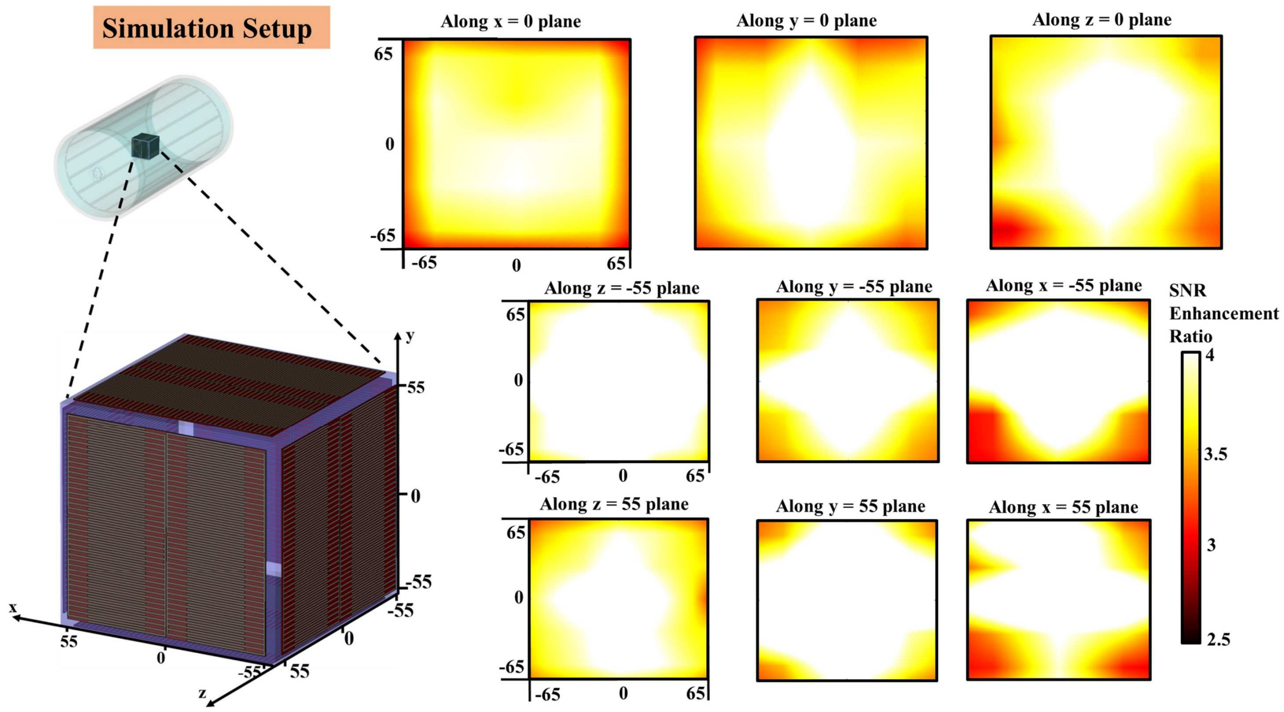

Fig. 2. A cuboidal phantom (130 mm × 130 mm × 130 mm) used for this study is covered with array of metasurface from all sides. SNR enhancement ratio is demonstrated inside the phantom along different planes (x, y, z) along 0, 55, and −55, respectively.

saline water is used to mimic the physical characteristics of a human body during simulation study [4]. All sides of the phantom are covered with a metasurface containing 2×2 unit cells, as shown in Fig. 2. The covered phantom is placed inside the birdcage coil which is commercially used in the MRI systems for RF excitation. They are widely used for transmitting RF pulses on the specimen undergoing scan and receiving signals for image reconstruction.

III. Results and Discussion

Interdigitated metasurface structures augment magnetic resonance imaging (MRI) field strength by enhancing the RF magnetic flux density, which in turn improves the SNR during MRI scans [5]. In addition, interdigitated metallo-dielectric metamaterials resonate as RF metasurfaces that enables the localization and enhancement of the RF magnetic field in 1.5T MRI [5]. This improvement in the SNR results in better image resolution and faster scanning times. Fig. 2. shows the designed simulation in CST Microwave Studio. The SNR can be calculated from the obtained enhancement in the received magnetic field (B_1^-) divided by absorbed power (P_{abs}) for 1A coil current as SNR$\propto B_1^-/\sqrt{P_{\text{abs}}}$ [6]. SNR enhancement ratio is calculated as the ratio of SNR with the metasurface to without the metasurface and the ratio has been shown with different planes ($x = 0, y = 0, z = 0$) over the entire phantom. Therefore, it can be concluded that the maximum SNR has been achieved at the center of the phantom as the interdigitated metasurface enables strong localization and enhancement of fields which can significantly boost the sensitivity and SNR. A uniform SNR of greater than 3 has been achieved across all the planes inside the phantom.

IV. Conclusion

This study presents a new way of visualising the SNR enhancement over the entire phantom focusing on the uniformity. This way of visualization can be helpful for further research in order to improve or fine tune the metasurfaces for MRI systems. The proposed metasurface has shown an enhancement of 4.5 times as the maximum and an almost uniform SNR (of greater than 3 times) over the entire phantom. Such a uniform enhancement in SNR throughout the phantom will enable a high-quality clinical diagnosis, even for human body extremities, for 1.5T MRI systems.

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