URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

A Single-Layer Metasurface Resonator for 3T MRI Local Signal Enhancement

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Abstract

Metamaterials, in particular 2D metasurfaces, offer great potential to advance the measurement efficiency in Magnetic Resonance Imaging (MRI). The signal-to-noise ratio (SNR) can be improved significantly in a multifold of applications.
One major drawback of MRI-compatible metamaterials usually is their bulky structure. This problem can be over–come by flat stripe-resonator metasurfaces.
Here, we take the next step and investigate the use of interdigital capacitors (ID) to electrically elongate the wires composing a single-layer metasurface resonator. A comprehensive study of the fundamental mode, which is of particular interest for MRI, is presented. To that end, the on-bench performance of two prototypes are compared, one of which is designed with the help of structural parallel-plate (PP) capacitors on two layers, while the second one uses the interdigital, single-layer version.
Although the adoption of interdigital capacitors simplifies prototyping, we observe that the quality factor drops significantly. However, ongoing MRI experiments show promising results, leading to significant SNR enhancement in the region of interest.

1 Introduction

Although MRI is being used and improved for more than five decades as the most versatile medical imaging modality, there still is a lot of potential to exploit its full capabilities. Mainly physiological restrictions are ham–pering the physically feasible developments. Thus, it becomes challenging to innovate and advance the imaging efficiency. Electromagnetic metamaterials are a promising solution in this respect since they allow substantial SNR enhancements [1]. A major drawback usually is the bulky design of such metamaterials, putting patient specific and/or conformal design for versatile applications beyond reach. However, the development of thin (sub-mm) dual-layer metasurfaces [2] overcomes these problems and is the first step towards even more advanced applications. Moreover, smart self-detuning strategies in the transmit phase of MRI allow to take care of patient safety at all times [2, 3]. The combination of both, thin metasurfaces and smart self-detuning, allow for the most advanced metasurfaces for MRI.
Here we advance the development by taking the next step towards single-layer metasurfaces, which can be manu–factured in a single step by a state-of-the-art laser etching process. These metasurfaces make use of interdigital capacitors [4], which replace the parallel-plate two-layer structures employed in [2].
The metasurface is composed of 14 wire-resonator unit cells (copper stripes) in a linear array, which is etched on RO4003 substrate (0.508 mm thickness) with the dimensions as shown in Fig. 1. We report on the design of the interdigital capacitors and characterization studies of the metasurface prototype. On-bench and MRI performance tests are conducted and the comparison to the PP case is presented.

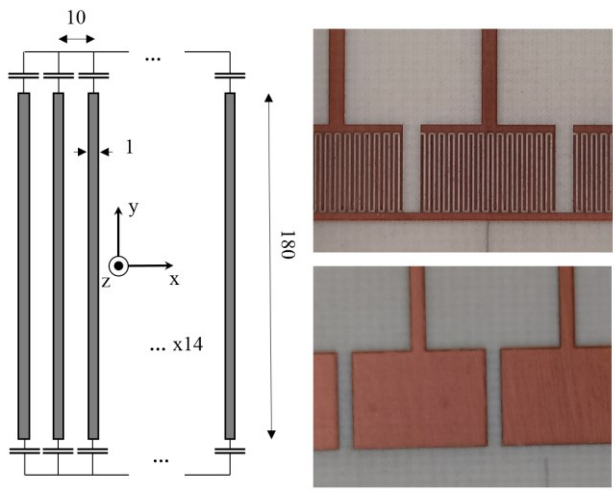

Figure 1. Schematic representation of the enhancement plate (lengths in mm) on the left, and details of the fabricated capacitors, ID and PP in right-top and right-bottom images respectively.

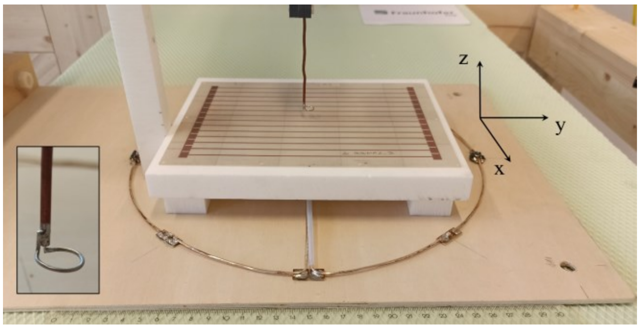

Figure 2. Measurement setup for mode characterization.

2 Interdigital Capacitor Design

The interdigital capacitors shown in Fig. 1 are composed of 28 copper fingers of about 5 mm length and 160 µm width each. The gap between fingers is also 160 µm. The total area occupied by each capacitor is 6.25 x 8.8 mm^2, which is almost the same as that of the rectangular patches in the PP-cap case, namely 6 x 9 mm^2. For the design, eigenmode simulations performed in CST Microwave 2019 were adopted after a first estimation of the capacitances [4]. Laser etching provides rapid prototyping capabilities. Note that for the PP-cap prototype, a ground stripe on the back layer (opposite of the patches in Fig. 1) needs to be added.

3 Performance of the ID-cap Metasurface

The resonance frequency and the quality factor of the ground mode were measured on-bench with the S_{21} dual-loop technique [5]. The ID plate has a quality factor of 130, almost half of 250 which is that of the PP plate, while the resonant frequencies are 128.6 MHz and 127.4 MHz respectively, intentionally higher than the target frequency to compensate for phantom loading. A compression of the higher order odd mode frequencies is observed in the latter case. To image the modes, a broadband tuned coil of 30 cm diameter excites the plate positioned at 4 cm above it, while a 10-mm sniffer loop was used to locally sample the S_{21} across a plane 1 cm from the plate, see Fig. 2. Scans across the symmetry planes of the setup were performed as well. For the mode of interest the maximum S_{21} is 1.2 dB lower in the ID case and the enhancement with respect to penetration depth is similar, Fig. 3(b-l). With regard to homogeneity perpendicularly to the stripes, the same behavior has been observed. Ongoing MRI measurements confirm the SNR enhancement due to the single-layer metasurface and will be presented.

5 Conclusions

We have experimentally shown the feasibility of a single-layer metasurface to spatially modulate the near field of a surface loop coil. The study paves the way towards the design of new imaging coils with integrated metasurfaces offering on-the-fly customizability. Flexible, conformal metasurfaces, as well as printable ones for patient-customized use will be investigated in the future.

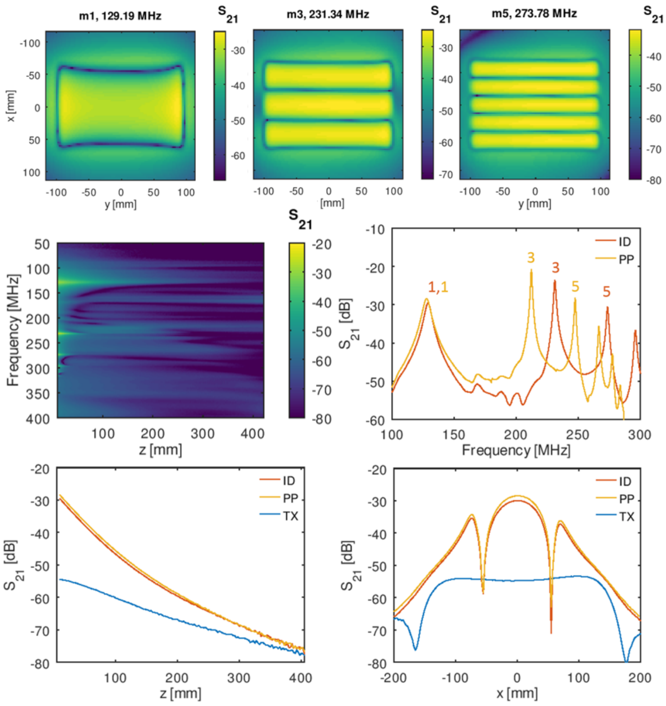

Figure 3. S_{21} maps of first three odd modes of the ID-plate 10 mm above the surface (top); $S_{21}(z)$, allowing observation of the different modes and their penetration depths (center-left), S_{21} at the center of the metasurfaces, with indicated mode numbers (center-right); S_{21} (z) for mode 1, TX refers to the coil only case (bottom-left), and S21 perpendicularly to the stripes at 10 mm height (bottom-right).

6 Acknowledgements

This work is supported by the Fraunhofer Internal Program (Grant No. MAVO 142- 600555). The authors want to thank Michael Jäger and Maik Hillmer for support in the production of prototypes and their characterization process.

7 References

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