Application of the SENSE Algorithm to Multimodal Switchable Metasurface Imaging

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Abstract. This work aims to provide a way of performing parallel imaging with a single-channel variable-frequency resonant device. Different spatial sensitivity profiles required for SENSE reconstruction are achieved by switching between the device eigenmodes. A device capable of such switching is manufactured and several k-spaces are acquired using the device different eigenmodes. The k-spaces are then subject to downsampling to obtain the sensitivity profiles of each eigenmode and then - to perform SENSE-based reconstruction of the unaliased images with different acceleration factors.

1. Introduction
Advances in material science have found practical realization in the development of a variety of new material classes. The radiofrequency (RF) engineering part of the magnetic resonance imaging (MRI) community has paid particular interest to metamaterials and high dielectric permittivity ceramics. These have found use in the scanner hardware development via a series of resonant devices used as RF coils for high and ultra-high field MRI [1, 2, 3, 4].

A common metasurface- or dielectric-based RF coil is a fixed-geometry resonant device supporting a number of eigenmodes with different frequencies and spatial electromagnetic field distributions [1, 2, 5]. In order for such a resonant device to be used in MRI its geometry is optimized in such way that a suitable eigenmode frequency is tuned to the resonant frequency of a target nucleus at the selected magnetic field strength. This commonly results in a highly-efficient fixed-frequency device [1, 2, 3], metamaterial a number of variable-frequency devices have also been suggested [4, 6, 7].

Excitation of the metasurface or dielectric resonator eigenmode tuned to the scanner operating frequency is often performed in MRI via coupling the designed device to the scanner body coil and using the latter both in transmission and reception modes [1, 4, 8, 3]. One drawback of such approach is in the lack of multi-channel capabilities. This, in turn, leads to the inability to perform parallel imaging with the designed resonant devices. This drawback is common among the fixed-frequency resonant devices due to their implicit tuning to a lowest order mode, providing highest spatial field homogeneity in the whole region of interest, whereas parallel imaging techniques require the same region of interest to be covered by a set of different spatially inhomogeneous receive field profiles.

This work aims to overcome this drawback by providing a technique for parallel imaging with a single variable-frequency resonant device, allowing receiving the NMR signal with different spatial sensitivity profiles. This is achieved by switching between the device eigenmodes and...
acquiring several reduced k-spaces using each of the eigenmodes sensitivity profiles to perform a common SENSE-based reconstruction [9].

2. Materials and Methods

In order to perform the desired eigenmode switching, a tunable metasurface was assembled to be used as an RF coil. The metasurface was fabricated as a printed circuit board (PCB) on an 210×300 mm² FR-4 substrate (Relative permittivity=4.6; Loss Tangent=0.02 @ 40 MHz). The substrate hosts 10 straight 10 mm wide copper traces with 12 mm gaps between them (Fig. 1). Two breaks were introduced symmetrically into the mid-points of the metasurface edge traces: one used for the connection of the coaxial cable and the other for a matching 50 Ohm resistance. This solution allows avoiding additional matching circuits and reduces the change of the input impedance during eigenmode switching. The short coaxial cable at one of the mid-points is then used to connect the metasurface to the MR-scanner low noise amplifier via an RF-trap.

Figure 1. Photo of the switchable metasurface with the connection ports, detuning circuits and switching mechanisms labelled.

Each trace is also equipped with a passive detuning circuit located at the edge of the PCB. The opposite edge of each trace hosts a group of capacitors and jumper-type switches used for changing the metasurface eigenmode frequencies. Frequency fine-tuning is implemented via additional variable high-Q capacitors located at the same edge of the PCB.

Imaging was performed on a 1 T Siemens Magnetom Harmony clinical whole-body scanner operating at the 40.5 MHz Larmor frequency. Five images of a homogeneous MRI phantom were sequentially acquired using the gradient echo FLASH pulse sequence with a 300×300 mm² field of view, a 256×256 points matrix and TR/TE = 100/10 ms. After each of the acquisitions the metasurface resonant frequency was adjusted using the jumper switches so that each image was acquired using a sensitivity profile resulting from the magnetic field distribution of a different eigenmode. The sensitivity profiles provided by each eigenmode can be seen in Fig. 2, G and H.

The image processing pipeline comprised spatial sensitivity estimation, k-space downsampling and SENSE-based reconstruction. Each mode sensitivity profiles were estimated from a low-resolution phantom image, acquired via cropping the 256×256 full k-space to the central 256×N_{profile} lines, where N_{profile} was varied from 16 to 64 central lines. Next, the full 256×256 k-space was downsampled to 256×(256/R), where R is the acceleration factor. This was performed by retaining only every Rth k-space line. Finally, the reduced k-spaces and the low-resolution sensitivity maps were reconstructed using the SENSE algorithm, as implemented
in the PULSAR toolbox [10] running under MATLAB 2020b. The reconstruction quality was assessed by computing the mean g-factor under various reconstruction conditions, particularly, under varying acceleration factors and number of eigenmodes (N) used for reconstruction.

3. Results

The SENSE method application to the aliased images resulting from the k-space downsampling provided a successful reconstruction of the full unaliased image with all the tested acceleration factors and mode selection conditions (Fig. 2). A qualitative image improvement as well as the mean g-factor reduction was observed with the increasing number of modes used for SENSE reconstruction (Fig. 3). Similarly, an increase in image quality (manifesting also in the decrease
in the mean g-factor) was observed with increasing sensitivity profile resolution (Fig. 4).

4. Conclusion
Current work shows a new principal way a single-channel limitation of the metamaterial or dielectric-based RF coils in MRI can be overcome, and parallel imaging can be performed. It was demonstrated, that acquiring the signal via the metasurface, serving as an RF coil, while tuning its different eigenmodes to the Larmor resonance frequency provides enough data for SENSE-based image reconstruction. While proof of principle has been demonstrated, true parallel imaging is yet to be performed, as, in the current work, images were acquired sequentially. The true parallel acquisition can nevertheless be attained due to a rather slow change in the acquired NMR signal relative to the modern electronic component switching times. Thus, in a single \( \frac{1}{(\text{acquisition bandwidth})} \) interval, the metasurface can be switched between different eigenmodes, and several k-space points might be recorded, so that different eigenmode k-spaces could be filled in an interleaved manner. This would allow the desired parallel imaging techniques to be applied to the data acquired in such a quasi-parallel interleaved technique.

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