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Numerical Investigation of a self-detuning Signal Enhancement Metasurface for 3T MRI

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Abstract

In this work, numerical simulation results regarding an automatically self-detuning signal enhancement plate (DSEP) for use in magnetic resonance imaging at 3T field are presented. The DSEP is composed of a linear alignment of wire resonators milled on a suitable PCB and inductively coupled to a varactor-loaded detuning loop. Eigenmode simulations allow to design the coupled system, whereas full-wave simulations of the device, excited by a circularly-polarized plane wave in the pres-ence of a phantom, show the detuning efficiency. In terms of H-field magnitude, a maximal enhancement factor of about four is observed at the target frequency of 123.5 MHz.

1 Introduction

Magnetic resonance imaging (MRI) is a powerful and non-invasive medical imaging technique. Due to the non-ionizing radiation, repetitive scans can be performed and it is also valuable for therapy planning and control in many cases. However, image quality depends strongly on the signal-to-noise ratio (SNR) which is improved by higher static main magnetic fields. In clinical environments, 1.5T and 3T MR scanners are the standards, whereas 7T tech-nology is currently more in a research phase although clinical use has been approved.

An alternative way to improve the SNR in MRI is picking up interest in recent years. So-called metamaterials and metasurfaces are custom-engineered electromagnetic (EM) materials that allow to shape, modify, and enhance EM fields in unprecedented ways [1]. They consist of a usually periodic arrangement of sub-wavelength structures, the meta-atoms or unit cells, which by collective action yield a macroscopic response and lead to exotic effective material properties not found in nature. Use of metamaterials in MRI allows for SNR enhancement and, thus, potentially provides an efficient way to improve the image quality and overall diagnostic efficiency [2, 3].

A signal enhancement plate (EP) can provide a local SNR increase by enhancing the radio frequency (RF) magnetic field during the transmission (Tx) and receive (Rx) phase in MRI. While the signal enhancement during the Rx phase is beneficial, the presence of the EP might also distort the excitation field during Tx phase and modify the targeted flip angle in the region of interest (ROI), which simply corresponds to a larger input power.

Since patient safety is utterly important, immense care must be taken when additional equipment is used inside the MR scanner. All safety protocols regarding applied power and temperature hot spots cannot detect the presence of additional structures. Hence, signal enhancement or modification during the Tx phase must be precisely controlled or at least switched off completely. On the contrary, during the Rx phase, the enhancement plate shall be tuned to the scanner's resonance frequency and perform

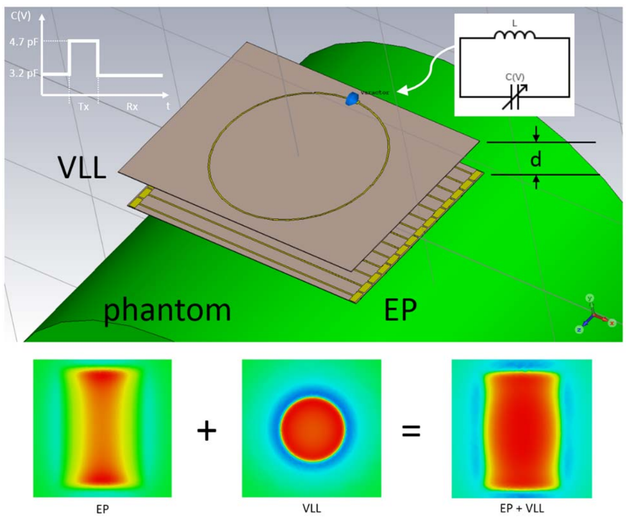

Figure 1. Sketch of the investigated Eigenmode problem. The DSEP is positioned 10 mm apart from a phantom (top). Illustration of the hybrid mode formation (bottom).

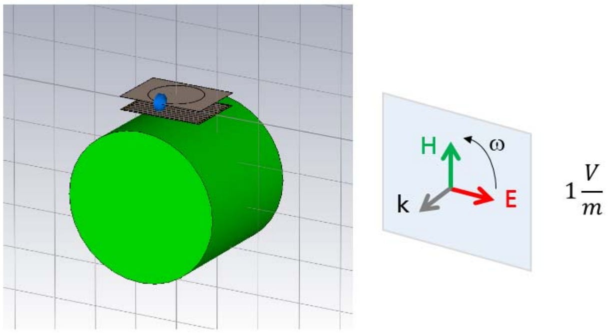

Figure 2. Full-wave model geometry and plane wave excitation depiction.

as expected. Obviously, detuning the EP precisely during the Tx phase solves this problem. Here, we suggest a coupled system that automatically detunes itself in the Tx phase due to the high incident power. In the Rx phase, however, the incident power is orders of magnitude lower and the combined structure acts as an EP for the MR signal.

2 Design of the DSEP

Our system is composed of i) a planar 2D metasurface consisting of closely-coupled capacitively-loaded resonant wires, and b) a varactor-loaded conductive loop (VLL), see Fig. 1. The composition of our structure is inspired by the work in Ref. [4], in which the authors design a non-linear structure via the coupling to a VLL. The hybrid eigenmodes that result from the coupling of the two structures can be used for signal enhancement purposes. An illustration of the lowest-order mode is presented in Fig.1 as well. If one of the subsystems, the least complex one in this case, can be passively detuned during the Tx phase, the hybrid mode would also detune allowing to achieve our goal.

For the VLL we slightly modified a structure reported in literature [4], and chose to redesign the EP to resonate at a suitable frequency. In the latter work, also targeting a 3T MR system, the varactor is modelled as a switchable capacitor of value 4.7 pF and 3.2 pF during the high incident power phase (Tx) and low power (Rx) phase, respectively. Such a simple model was deemed sufficient for a preliminary study, though a thorough characterization of the varactor's behavior is under way. The detuning loop, milled on a similar substrate as the EP has a radius of 60 mm and a 1 mm wire width. A gap and soldering pads were added subsequently with a lumped element capacitor in between modelling the varactor in CST Microwave Studio (Dassault Systemès). Eigenmode simulations show that the VLL alone resonates at 131.4 MHz and 110 MHz for a loading capacitance of 3.2 pF and 4.7 pF, respectively.

On the other hand, the EP is composed of an alignment of N closely coupled λ/2-length wires and supports N-1 hybrid eigenmodes [2, 3], but only the lowest order mode is of interest here. To electrically shorten the resonant wires, capacitive patches were milled on the same layer of a RO4003C substrate with appropriate grounding on the other side. By varying the length of the capacitive patches, the EP can be tuned to the desired resonance frequency. A parametric sweep in an eigenmode analysis of the complete system allows to tune the hybrid mode to the operational frequency of an available 3T scanner (MAGNETOM Skyra, Siemens Healthineers), which is 123.5 MHz. The EP is made of 14 copper stripes 180 mm long and 1-mm wide at a distance of 10 mm from each-other. The capacitive patches are 9 mm wide and 5 mm long. The EP alone resonates at about 141 MHz.

Finally, eigenmode simulations of the complete system show that the hybrid mode resonates at 123.45 MHz for a varactor value of 3.2 pF and 147.26 MHz for 4.7 pF, indicating an effective detuning of the device. Some fine tuning was carried out by varying the distance between the two PCBs. The best result was achieved for a distance *d* of 30 mm. In contrast to the approach in Ref. [4], our EP design is thin since it is milled on a PCB with a thickness below 1 mm. In their work, the authors used a helical structure for the metamaterial unit cells which is about 2.5 cm in height.

3 Device Performance in Simulation

Full-wave simulations were performed to evaluate device's performance. To better model the excitation of a realistic B_1 field, but still keep the CST model simple and computationally reasonable, a circularly polarized plane wave is used to excite the structure, see Fig. 2 for the orientation of the field components. The wave vector is in the plane of the structure, such that the electric field is aligned with the wires and the magnetic field is orthogonal to the structure. Open boundary conditions were adopted to truncate the simulation domain. The DSEP is positioned such that the EP is aligned with the center of the reference system at a distance of 10 mm from the nearest extremity of the phantom. The phantom has a diameter of 350 mm and an axial extent of 200 mm, related to the dimensions an available homogenous MR phantom for later experi-

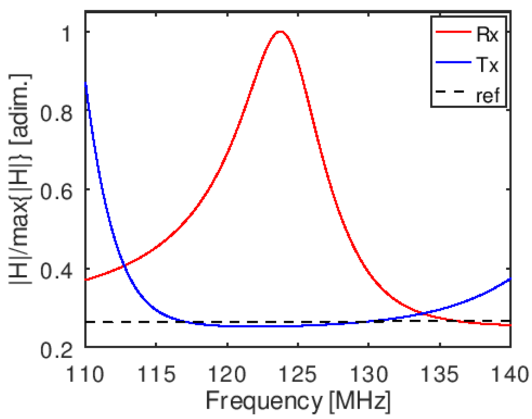

Figure 3. Normalized H-field magnitude at the phantom's surface for the Rx, C_V = 3.2 pF (red), Tx, C_V = 4.7 pF (blue), and the reference (dotted) case.

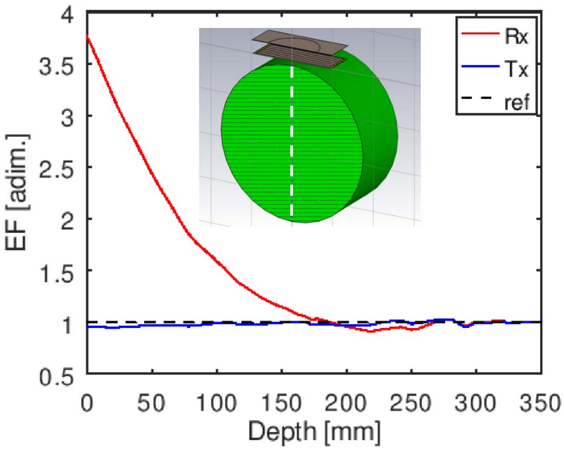

Figure 4. Simulation results for the field enhancement factor along the white dotted line in the inset at the operational frequency of 123.5 MHz.

ments. For the phantom, we use agar material with a relative permittivity of 70 and a conductivity of 0.7 S/m [4]. The frequency domain solver with adaptive mesh refinement was deemed appropriate for the task.

Simple H-field probes are positioned at different depths inside the phantom in the direction perpendicular to the DSEP. In Fig. 3, the magnitude of the normalized H field at the phantom's surface is shown. The detuning during the Tx phase can be clearly observed, although the presence of the VLL introduces some slight attenuation of the Tx field as can be seen by comparison to the reference line. The maximum field enhancement factor is 3.77 and occurs at 123.74 MHz. This slight difference with respect to the eigenmode simulations might be due to the fact that the RF shield is not present in the full-wave simulations. The enhancement factor dependending on the penetration depth at 123.4 MHz is presented in Fig. 4. Due to the decay of the mode perpendicularly to the plane of the plate, there can be an enhancement up to adepth of about 175 mm during the Rx phase, while there is very small attenuation in the Tx phase. This maximal depth is related to the dimension of the EP.

Regarding the simulation outcomes, we can qualitatively reproduce results in Ref. [4] but our design of the EP is very thin since it is manufactured on a PCB with a thickness below 1 mm. For later MRI applications in which available space in small, or to employ conformal structures in, e.g., head coils, this is an advantage.

4 Conclusions

A self-detuning signal enhancement device composed of a wire resonator metasurface and a varactor-loaded conducting loop has been presented. The system is designed and fine-tuned to operate in a 3T MR scanner environment. Numerical simulations show the detuning during the transmission phase which is important for maintaining patient safety in MRI applications with metamaterial-induced signal enhancement. During the Rx phase, the system supports a hybrid mode resonating at 123.5 MHz leading to a field enhancement by a factor larger than three. The penetration depth is shown to coincide with the lateral dimension of the enhancement plate.

A first prototype of the simulated DSEP is being manufactured and preliminary lab measurements are ongoing. In the next step, an iterated design will be manufactured and tested in the MR scanner. A custom-made measurement protocol allows to separate effects on the Tx and Rx signals.
Among others, field homogeneity in planes parallel to the DSEP has to be assessed. Moreover, we will extent the detuning mechanism presented here to other metamaterial devices which are to remain silent during the Tx phase in MRI.

5 Acknowledgements

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6 References

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