Volume metasolenoid-based coil for $^{23}$Na MRI at 7 Tesla

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Abstract. In this work, we demonstrate a novel X-nuclei radiofrequency coil design aimed for ultra-high field magnetic resonance imaging. The proposed design is based on a set of coupled split-loop resonators, forming a so-called metasolenoid, fed via inductive coupling by a non-resonant loop. Due to the fundamental mode excitation in the metasolenoid the homogeneous RF magnetic field inside its inner volume is provided. $^{23}$Na RF coil for human wrist imaging at 7 Tesla based on the proposed approach is demonstrated and investigated numerically. The design is compared with a commercially available volume birdcage coil. The comparative study revealed 60% improvement of SAR efficiency of metasolenoid coil operating in the linearly-polarized mode over the birdcage coil driven in the circularly polarized mode.

1. Introduction
Magnetic resonance (MR) is widely used for biomedical applications employing X-nuclei (i.e. other than hydrogen) imaging and spectroscopy. Inherently, non-hydrogen studies are challenging due to low concentration of X-nuclei in the region of interest and thus low signal-to-noise ratio (SNR) of the corresponding image or spectra. From the MR equipment perspective, SNR in the receive mode and excitation efficiencies in the transmit mode depend mainly on radiofrequency (RF) coil design. RF coils are used in MR studies for establishing a homogeneous RF magnetic field in the region of interest (ROI) and for spatially-uniform and efficient detection of the nuclei response. The ultimate coil sensitivity in the receive mode allows to obtain high MR image and spectrum quality. Ultra-high field (UHF) imaging and spectroscopy provide straightforward solution for an SNR improvement resulted from the static magnetic field enhancement which is disadvantageously accompanied with additional limitations to RF coil design related to safety and transmit field inhomogeneity. Specifically, for extremity imaging, carefully designed local dedicated coils are used both in the transmit and receive modes. Existing commercially available solutions for extremity imaging at UHF are basically volume resonator coils (i.e. birdcages [1],[2]) that are cylindrical resonators based on multiple capacitively-connected parallel copper rungs. In order to maximize SNR of X-nuclei imaging, birdcage coils are driven in quadrature using two orthogonal linear modes of the birdcage resonator through a 90-degrees hybrid coupler.

In this contribution, we propose an alternative RF coil design for 7 T $^{23}$Na wrist imaging which uses the fundamental eigenmode of the metasolenoid linearly-polarized resonator consisting of coupled split-loop resonators. The proposed coil was studied by full-wave simulations and a
2. Design and numerical simulation

Beneficial properties of the coupled split-loop resonators (SLRs) forming a so-called metasolenoid 1.5 T MR imaging were recently shown in [2]. The authors demonstrated a wireless SLR coil which was used for extremity imaging by the inductive coupling to the external volume body coil. In contrast, here we propose to drive a metasolenoid by inductive coupling to the non-resonant loop fed by the 50 Ohm port connected to the transceiver of 7 T MR system through a matched coaxial cable (Figure 1a). The SLR dimensions 12 × 20 cm are chosen to fit the targeted imaging volume of a human wrist. The coil resonator comprises a set of 12 copper SLRs of the thickness 1 mm periodically arranged at 1.5 cm with respect to each other. The stack of inductively coupled SLRs produces a metasolenoid resonator [4], which possesses a number of eigenmodes at the certain eigenfrequencies with different RF magnetic field distributions. The fundamental volume mode with the opposite current directions on the top and bottom conductors of the SLRs creates the most homogeneous RF magnetic field within the metasolenoid. Due to the homogeneity in the volume of interest, this mode can be used for UHF imaging. To tune the mode to the Larmor frequency of $^{23}$Na at 7 Tesla (78.8 MHz) lumped capacitors (8 pF) are embedded in two gaps of each SLR as depicted in Figure 1a. The resonator modes were studied numerically using Eigemode Solver of CST Microwave Studio 2017. The eigenmode simulation was made in the lossless approximation assuming perfect electric conductors of the SLRs and ideal capacitors with zero series resistance. The magnetic field distribution in the central longitudinal plane of the resonator corresponding to its fundamental volume mode tuned to 78.8 MHz is illustrated in Figure 1b. According to this field pattern the metasolenoid behaves similarly to a conventional wire solenoid coil as it provides substantially linearly polarized magnetic field along $y$-axis. However, the metasolenoid coil has no electric currents flowing in $y$-direction. As a result, the distribution of E-field of this coil and its specific absorption rate (SAR) may considerably differ from a conventional solenoid and from other coils used for wrist imaging. Moreover, the proposed coil has an advantage of tuning to the Larmor frequency over a conventional solenoid. Indeed, it is possible to show that there is no possibility to build the solenoid coil of the considered size tuned to 78.8 MHz since its self-resonance occurs already at around 18 MHz which was checked numerically.

Figure 1. Proposed metasolenoid X-nuclei coil for 7T coil (a) and the fundamental mode magnetic field distribution in central longitudinal plane of the resonator voxelized model of human arm. A comparison with a commercially available birdcage coil for $^{23}$Na wrist imaging was made.
In order to demonstrate capabilities of the proposed coil, the metasolenoid was simulated together with the non-resonant inductively coupled feeding loop (Figure 1a). The loop has the same size as the SRR’s and is driven in the simulation by the 50-Ohm discrete port. The simulations were performed in CST Microwave Studio 2017 using Time Domain Solver. The resonator as well as the feeding loop were implemented as copper wires of the diameter 1 mm while losses in lumped capacitors were taken into account by equivalent series resistance of 0.05 Ohm. Since the proposed coil design was aimed for wrist imaging the simulation model contained the voxel model of a human arm.

For comparison, a commercially available circularly polarized high-pass birdcage coil was simulated with the same method. The birdcage had the length of 27 cm and a radius of 11 cm. Its fundamental mode was tuned to 78.8 MHz by lumped capacitors (125 pF). The birdcage coil had 8 copper rings of the widths 35 mm. The coil was driven in the quadrature mode via two orthogonal 50-Ohm lumped ports enabling circular polarization of the magnetic field in the arm.

The transmit $B_1^+$ magnetic field was calculated both for the metasolenoid and birdcage coils. In order to take into account safety aspects local SAR within the voxel model was also calculated. Figure 2 illustrates the SAR efficiency ($B_1^+/\sqrt{\text{SAR}_{\text{max}}}$) in the central transverse plane of birdcage coil (a) and metasolenoid coil (b). According to the obtained field patterns both coils create homogeneous field distributions within the arm. Beneficially, the metasolenoid coil provides 60% improvement of SAR efficiency within the ROI (6.4 for the metasolenoid coil versus 4 $\mu T \cdot \sqrt{\text{kg}}/\sqrt{\text{W}}$ for the birdcage coil). In addition, despite of only one polarization of the proposed coil, it gives 2.8 times higher $B_1^+$ for the same accepted power than the birdcage. It means, the transmit efficiency and SNR of the proposed linearly-polarized coils are higher than ones of the circularly polarized coil. Another advantage of metasolenoid is the possibility of a higher-order mode excitation which can be used for realization of an additional frequency channel and enabling the dual-frequency coil operation. This approach may be useful is obtaining for instance anatomical reference images of the scanning object at the hydrogen frequency of 300 MHz.

![Figure 2. Simulated $B_1^+/\sqrt{\text{SAR}_{\text{max}}}$ distributions ($\mu T \cdot \sqrt{\text{kg}}/\sqrt{\text{W}}$) in central transverse plane of the birdcage coil (a) and the proposed coil (b).](image-url)
3. Conclusion
In this work, we proposed and numerically studied a new X-nuclei RF-coil for human wrist imaging at 7 T. Comprising a set of coupled split-loops (the metasolenoid resonator) fed by non-resonant loop, the coil for \(^{23}\)Na wrist imaging provided 2.8 times higher transmit and 60% higher SAR efficiency over a commercially available circularly-polarized birdcage coil in the region of interest. Additionally, dual-band operation of the coil can be obtained using the higher order modes of the resonator. The dual-band operation is necessary to obtain an anatomical reference (based on hydrogen MRI) that must always accompany a sodium MRI.

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