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We propose the dual-tuned volume coil for magnetic resonance imaging at two nuclei. This coil is based on the combination of two independent metasurfaces that can be used simultaneously for fluorine and hydrogen $^{19}F/^{1}H$ imaging at 7 Tesla for small animals. Each metasurface is made of non-magnetic metallic rods and structural capacities of etched metal strips. The geometry is chosen so that two modes supported by the two metasurfaces resonate at the required frequencies 282.6/300.1 MHz. The two metasurfaces can be tuned independently by mechanically adjusting the length of the two sets of wires. We have numerically studied the concept of the proposed dual-tuned coil.

1 Introduction

Nowadays, Magnetic Resonance imagining is an essential apparatus in biology and medicine. This technique allows to provide 3D in-vivo anatomical images based on Larmor precession of the hydrogen nuclei (^{1}H) under a strong static magnetic field. Complementary information can be obtained by probing nuclear magnetic resonance signals of spins of other nuclei. For instance fluorine-19 (^{19}F) is used as a component of several contrast agents [1] allowing an accurate monitoring and tracking of injected cells into a body [1]. However, due to weak concentration of fluorine, ultrahigh-field MRI scanners are required to reach a sufficient signal to noise ratio (SNR). Moreover, as the Larmor frequency (i.e. the frequency of the nuclear magnetic resonance of spins) for the same magnetic field strengths depends on the nuclei type, dual-nuclei imaging requires a dual-tuned coil.

Recently it has been shown that hybridized resonators can improve the radio frequency (RF) field homogeneity and signal-to-noise ratio in the case of a single-nuclei application at 7 T [2]. Also, it has been proposed to excite two different modes of two hybridized wires structure with an electrically small loop antenna connected to MRI scanner only with one feeding channel [3]. A similar structure has been proposed later for the realization of a surface coil that operates at two independent frequencies providing independent tuning and matching [4].

In this paper, we propose a volume receive/transmit MRI antenna based on two independent metasurfaces that can be used simultaneously for fluorine and hydrogen $^{1}H/^{19}F$ imaging of a small animal at 7 Tesla. The proposed dual-tuned coil can be tuned independently to the desired Larmor frequencies by adjusting the length of two sets of periodic telescopic wires located on cylindrical surfaces surrounding a subject to be scanned. This approach of tuning avoids the use of additional electronic elements and insertion losses of the latter. Thus, performance of the coil (i.e. quality of images) can be increased, meantime the price of manufacturing can be reduced. Our design is quite different to classical dual-tuned birdcages working as a combination of low-pass and high-pass birdcages for high-field MRI applications [5]. Such dual-tuned birdcages work well only when the two corresponding Larmor frequencies are considerably different, for instance $^{1}H/^{31}P$. [5].

2 Coil design

The considered coil consists of two intricate 1D metasurfaces where the last unit cell is connected to the first one, forming a cylinder. The first metasurface behaves as a left-handed transmission line (LHTL). Actually, this structure corresponds to a high-pass birdcage structure proposed by Cecil Hayes in 1985 [6]. A conventional birdcage is very convenient for single-nuclei imaging because its fundamental mode provides homogeneous magnetic field inside the whole sample. In this work, we propose to use such a LHTL called birdcage-like metasurface (see Fig. 1a) for fluorine imaging. It consists of 6 legs (i.e. thin conductors directed along the cylindrical axis). The legs are repeated with the angular period 60° around a 40mm-radius circumference of the cylinder. Each leg is made of two brass tubes with radius 1 mm and 0.75 mm to obtain a telescopic conductor with a mechanically adjustable length. On one side of the structure, the legs are interconnected by capacitors[7] and are short circuited to each other on the other side. The capacitors are etched on low-loss dielectric substrate Rogers 4003 ($\epsilon = 3.38$ and $\delta = 0.0021$) with thickness 0.508 mm. The part of the coil that is sensitive to the response of protons at 300.1MHz consists of an array of split ring resonators (SRRs), namely 6 split rectangular loops distributed along a circle of radius 30mm. The shape of the SRRs is rectangular with dimensions of 97 mm by 10 mm. The coupling between SRRs has been studied previously[8, 9]. The relative orientation between SRRs changes the mutual inductance between them. It is positive when they are parallel or negative if coplanar [8]. As in the previous metasurface each SRR is telescopic, i.e., made of the assembly of 2 mm tube and 1.5 mm one. At one end, two wires are connected through a distributed capacity which is made of copper traces printed on a low-loss substrate (Rogers 4003). SRRs generate homogenous magnetic field is at the lowest frequency among the modes of the same metasurface. Schematic view of the split-ring resonators is shown in Fig. 1b.

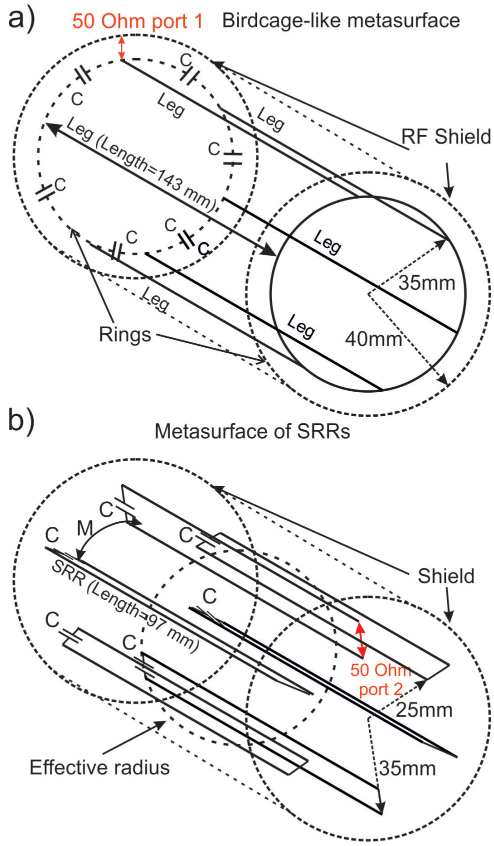

Figure 1: Schematic view of two metasurfaces comprising the proposed coil: (a) the metasurface of wires (the birdcage-like metasurface); (b) the metasurface of coupled split-ring resonators (the metasurface of SRRs).

3 Numerical simulations

First, we test numerically the two structures separately using commercial software for 3d electromagnetic simulations CST Microwave Studio 2018 (Frequency domain solver). All wires were placed along Z-axis, axis of an MRI bore. Both metasurface-based coils have been shielded by a cylindrical PEC with diameter 80 mm. The 50 Ohm excitation port for the birdcage-like metasurface is connected between one leg and shield (port 1). To excite the array of SRRs, we use a 50 Ohm port connected in the gap of one SRRs (port 2). Both structures have been loaded by a cylindrical homogeneous phantom made of 60% $2-2$-trifluoroethanol and 40% water ($\epsilon = 39$ and $\delta = 0.06$). Its radius and length are equal to 12.5 mm and 75 mm, respectively. These values are related to typical small animal's sizes. Further, region of interest (ROI) corresponds to the phantom. All structures have been adjusted to work at desired frequencies of fluorine and hydrogen at 7 Tesla (282.6/300.1MHz) by adjusting the length of telescopic wires. The adjusted values are 143 mm and 97 mm, respectively. Also, the

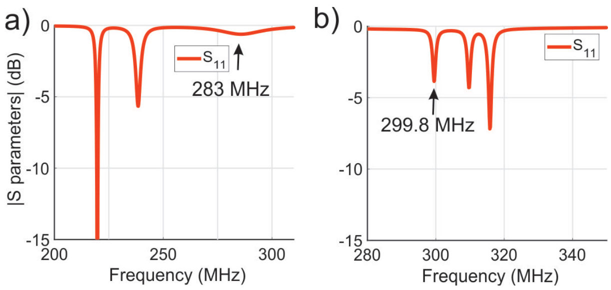

Figure 2: S11 (reflection coefficient) of simulated structures loaded by the phantom: (a) the birdcage-like metasurface; (b) the metasurface of SRRs.

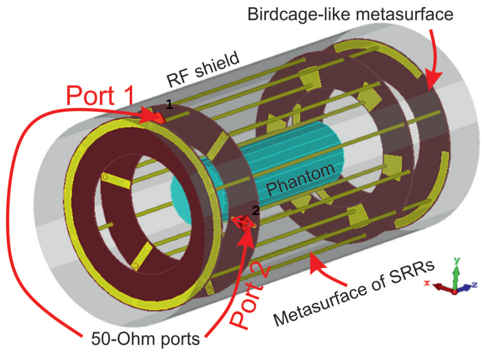

Figure 4: General view of the dual-tuned coil loaded by the phantom.

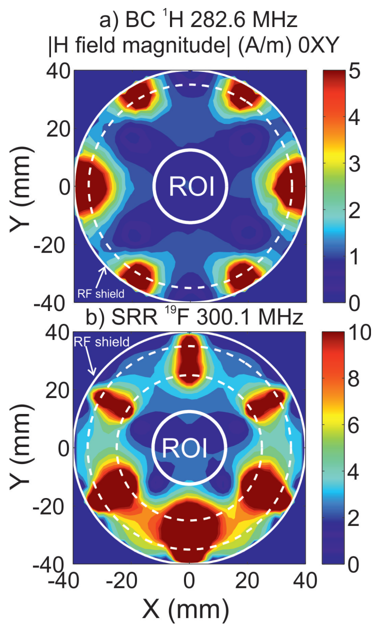

Figure 3: Amplitude of magnetic field inside the coil in central transverse plane ($z = 0$): (a) mode of the birdcage-like metasurface at $282.6 MHz$; (b) mode of the metasurface of SRRs at $300.1 MHz$. The ROI is related to the cylindrical phantom used in the simulation.

overlapping between two parallel metallic plates of the connecting the wires at their ends has been adjusted to achieve preliminary frequencies tuning of both structures. Parameters of the structures are shown in Fig. 1a and b. respectively. S-parameters and magnetic field patterns are presented in Fig. 2 and Fig. 3 respectively. At both frequencies we are exciting the fundamental mode of the structures generating homogeneous magnetic field inside the coil, i.e., inside the region of interest (ROI).

Next, both metasurfaces are combined into the same coil to work simultaneously at the two frequencies. Here, the metasurface of SRR is closed to external surface of the phantom, meantime the radius of the birdcage-like metasurface is equal to outer radius of the metasurface of SRR. Dimensions of both metasurfaces limited by the RF shield that can not be bigger then 80 mm due to the size of MRI bore. Also, decreasing of the radius of birdcage-like metasurface increase the mutual coupling between two metasurfaces. The final geometry of the dual-tuned coil is presented in Fig. 4. The final setup including the RF shield and the phantom is not changed. In case of this combined coil all its dimensions coincide with ones of the two independently optimized single-tuned metasurfaces (see Fig. 1). In the Fig. 5 the S-parameters of combined structures are presented. Both structures seems to be not very sensitive to each other and their frequency shift after combining is negligible due to orthogonality of the modes. The slight variation of the resonant frequencies can be compensated by changing the length of telescopic wires.

As it was previously mentioned, the proposed coil maintains independent tunability of the resonant frequencies. In this case it is possible to reduce the number of elements of tuning and matching circuits and keep only one capacitor for each channel only for matching. In this case SNR of the images of the sample can be increased. S - parameters of independent tuning study are presented in Fig. 6. Initial S - parameters of the coil are presented in Fig. 6a. If the length of the metasurface of SRRs is modified, it affects mainly S_{22} (Fig. 6b). Here, changing of S_{11} can be neglected. In the opposite case (Fig. 6c) when the length of SRRs is initial and the length of the birdcage-like metasurface is modified it affects

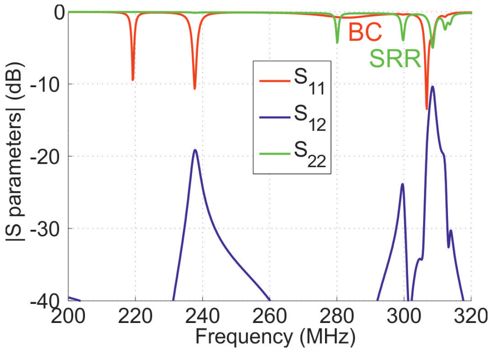

Figure 5: S-parameters of the combined dual-tuned coil loaded by the phantom.

mainly S_{11}. Finally the dual-tuned coil tuned for the two desired Larmor frequencies of ^{1}H and ^{19}F is obtained. Contrary to conventional coils that require a matching/tuning circuit, here only a matching element, i.e. one tunable capacitor per channel is required.

4 Efficiency of the coil

To analyze the efficiency of the coil we have calculated B_1^+ (clockwise circularly polarized) magnetic field distribution and have plotted it inside the ROI. In this case, the coil has been matched by capacitors and tuned by length adjustment for desired frequencies. To achieve a good matching level at 282.6/300.1 MHz, we use two tunable capacitors. The values of them are 2.55 pF and 14.07pF for the birdcage-like metasurface and for the metasurface of SRRs structures, respectively. Ohmic losses in these capacitors were taken into account (0.35 Ohm and 0.15 Ohm series resistance respectively). These two values are deduced from the quality factor of commercially available capacitors which is typically equal to 1000 in this frequency range and for these capacitance values. In this case, the reflection coefficient $|S_{11}|$ and $|S_{22}|$ are less than -10dB. The level of parasitic transmission coefficient between the two ports is low. Indeed, $|S_{12}|$ is smaller than -15dB. Calculated field pattern inside the phantom are presented in Fig. 7a for birdcage-like metasurface and in Fig. 7b for SRRs. In case of fluorine ($282.6MHz$) a very good homogeneity of B_1^+ field inside the region of interest is obtained (the birdcage-like metasurface). Indeed, the standard deviation of the field is equal to $0.04\mu T$. At the $300.1MHz$, (the metasurface of SRRs), the field is less homogenous with a standard deviation of

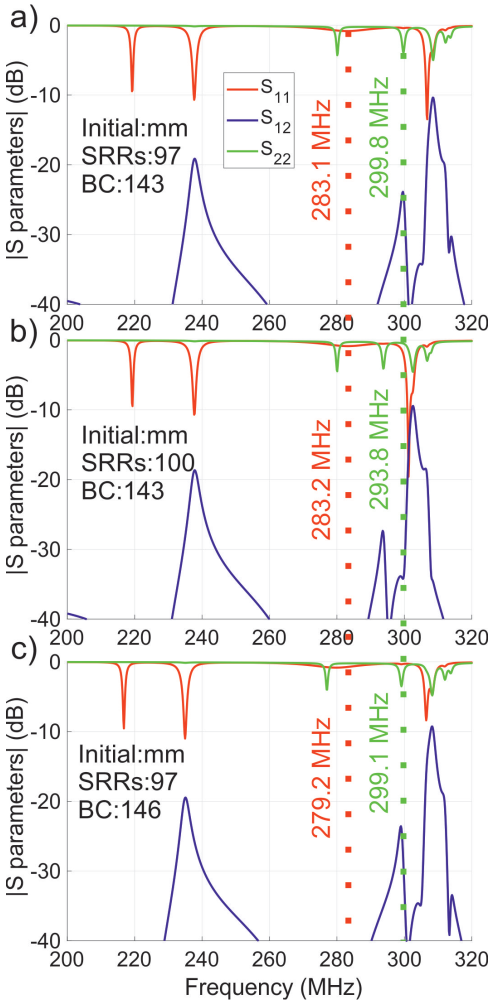

Figure 6: Study of independent tuning: (a) initial S-parameters of the dual-tuned coil; (b) length of the metasurface of SRRs have been changed; (c) length of the birdcage-like metasurface have been changed.

$0.32\mu T$. However, this value is still sufficient for MRI preclinical application. This heterogeneity of the field can be explained by the interaction between two structures and by the presence of the phantom.

5 Conclusion

In this work we have proposed the new design of the dual-tuned volume coil based on closed 1D metasurfaces. We have shown a numerical study of the proposed geometry with a Finite Element Method solver. The homogeneity of B_1^+ field at the two se-

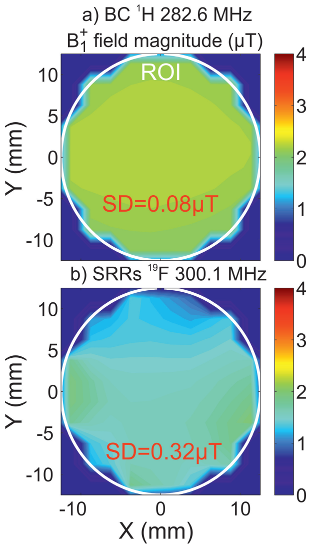

Figure 7: Magnitude of B_1^+ at $z = 0$ inside the ROI (phantom): (a) the birdcage-like metasurface; (b) the metasurface of SRRs.

lected Larmor frequencies is enough for preclinical imaging. Also, a good matching has been achieved with a high isolation between two ports. We are currently making a prototype to validate this coil experimentally.

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