Dual-frequency RF coil for $^{1}H/^{19}F$ Preclinical 9.4T MRI of Small-animal Lungs

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***Abstract*—A radiofrequency coil based on periodic resonant structure for 9.4T preclinical magnetic resonance imaging has been developed. Proposed coil allows the study of fluorine and hydrogen content in mice's lungs using resonant excitation of two mutually orthogonal eigenmodes in the resonant structure at two Larmor frequencies of 376 MHz (^{19}F) and 400 MHz (^{1}H) simultaneously. The proposed radiofrequency coil can be tuned to different Larmor frequencies by changing the tuning capacity values and, therefore, is suitable for other multi-nuclei imaging applications.**

Keywords—magnetic resonance imaging, radiofrequency coil, dual-tuned RF coil, preclinical applications, ultra-high field MRI

I. Introduction

Magnetic resonance imaging (MRI) is a non-invasive method for studying an internal structure of biological tissues. MRI is an actively developing area of clinical and preclinical diagnostics. In MRI, radiofrequency (RF) coils excite and detect signals from nuclei with non-zero spin at the Larmor frequency in a strong static magnetic field [1]. Ultra-high field (UHF) MRI (with a static magnetic field $B_0 \geq 7$ T) is a valuable research method for preclinical applications due to high signal-to-noise ratio (SNR) values of obtained images and possibility of multinuclear studies available in most of preclinical MR scanners [2]. In preclinical UHF MRI local dedicated transceiver RF coils are commonly used. In order to perform multinuclear studies it is required to use RF coils tuned simultaneously to several resonant frequencies. Dual-tuned coils are mostly used operating at the Larmor frequencies of hydrogen (^{1}H) and specific nucleus (X-nucleus) of interest for the certain preclinical study. It is required to obtain a high SNR at X-nucleus since their concentration in tissues is very small compared to ^{1}H. Therefore, RF coils for preclinical applications are commonly designed as dedicated coils with RF magnetic field covering the specific organ or tissue.

Preclinical studies are important to study pathological processes in biological tissues and organs. Particularly, lung diseases accompanied by tissue fibrosis could be investigated using preclinical studies of small animals (i.e. mice) for further application in clinical practice. Of particular interest are multinuclear studies of lungs: using the magnetic resonance of specific nuclei such as ^{129}Xe or ^{19}F, one can obtain additional information about the structure of lung tissues. Thus, fibrosis of lung tissues can be investigated using ^{19}F MRI together with ^{1}H imaging which is used to obtain an anatomical picture of the lungs [3].

RF coils for multinuclear MRI basically operate at hydrogen and X-nucleus Larmor frequencies simultaneously [4]. Moreover, preclinical coils must be compatible with other equipment of MR scanner and work inside a narrow shielded bore [5].

RF coil for small-animal MRI can be volumetric (i.e. solenoid, saddle coil, birdcage) [4, 9] or surface configuration based on loops or stripline [5, 6, 10, 11]. A periodic resonant structure-based design could be also used to create an RF coil for small-animal imaging. Such coils comprise arrays of parallel thin wires with distributed capacity, operating using hybridized eigenmodes [6–9, 11]. Particularly, RF coil based on two curved periodic structures of thin metal wires with distributed capacity was proposed operating at Larmor frequencies of ^{1}H and ^{31}P by two orthogonal hybridized eigenmodes [9]. Another approach to create a dual-frequency surface RF coil is based on using of two separate coplanar resonant loops in the specific case tuned to the Larmor frequencies of ^{1}H and ^{23}N for the purpose of preclinical MRI of the mouse brain [10]. Another example of a dual-frequency preclinical RF coil is based on a pair of thin-wire surface resonators [11]. Operation of the RF coil is due to the resonant excitation of two different eigenmodes at Larmor frequencies of ^{1}H and ^{19}F in two mutually orthogonal periodic arrays of parallel thin metal strips used for full-body mouse imaging.

The goal of this work is to use the approach of thin-wire resonator eigenmodes excitation to develop a transceiver RF coil with two independent frequency channels allowing simultaneous multi-frequency operation for preclinical 9.4 T ^{19}F and ^{1}H MRI of a mouse lungs.

II. RF Coil Design

Fibrosis of the lung tissue can be seen with ^{19}F MRI, but to obtain an anatomical image of the lungs ^{1}H MRI is required. Superposition of ^{19}F and ^{1}H images gives complex practically valuable information about lungs structure.

The proposed $^{19}F/^{1}H$ RF coil design include a resonator comprising nine parallel equidistantly located thin conductors connected to each other at their both ends by common conductors via lumped capacitors according a low-pass configuration [12]. All conductors are made of copper strips on a thin and flexible curved dielectric FR-4 substrate located over cylindrical surface with the radius of 32 mm. The conductors' width is 1 mm, and the distance between adjacent conductors is 2 mm. Fig. 1 shows a general view of the proposed RF coil.

Dual-frequency RF coil works by exciting orthogonal eigenmodes in a resonator consisting of parallel thin metal strips with two independent RF sources. One of those excites a resonance at a Larmor frequency of ^{19}F, the other one is responsible for excitation of the resonance at ^{1}H. In a thin-wire resonator N = 9 eigenmodes can be excited and in the

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proposed coil the modes of the first and second orders are used at ^{19}F and ^{1}H Larmor frequencies respectively. Constant value capacitors of C_1=5 pF are used to tune the resonator to desired frequencies. Tuning capacitors with C_2=10 pF are included in the gaps of central conductor to tune independently the second eigenmode to the ^{1}H frequency. When the second mode is excited, there is a current in the central conductor, which is not the case while the first mode is excited. Therefore, the eigenmodes are intrinsically decoupled.

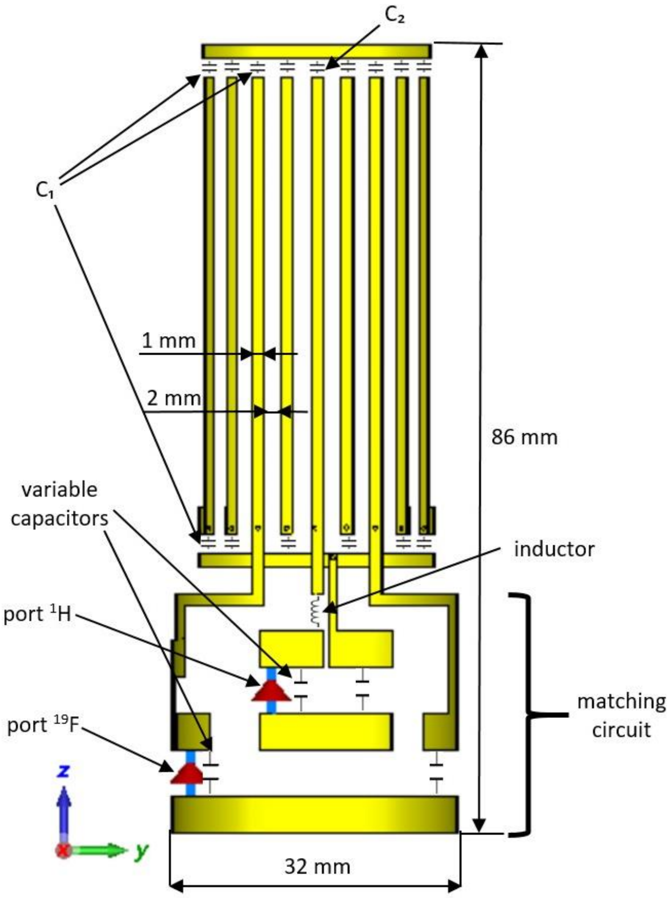

Fig. 1. General view of the proposed RF coil

Fig. 2 shows the schematic of the proposed RF coil including two impedance matching circuits in ^{19}F and ^{1}H inputs of the coil.

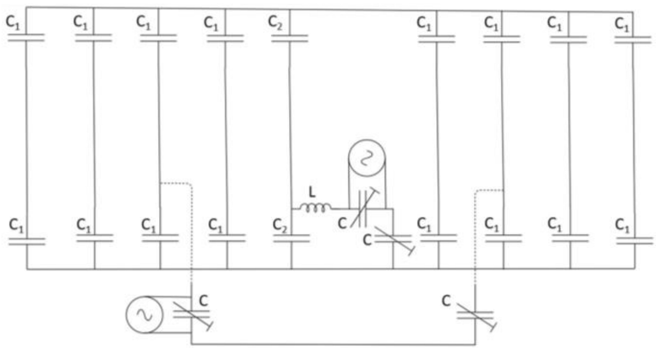

Fig. 2. Schematic of the proposed RF coil

III. Numerical Simulations

For electromagnetic simulations, Frequency Domain solver of CST Studio Suite 2021 (Dassault Systèmes, France) was used. The RF coil was simulated with an elliptical phantom having averaged material parameters of mouse lungs (electric conductivity σ = 0.4 S/m, relative permittivity ε = 40) and a copper cylinder with a diameter of 20 mm and a length of 100 mm to represent the RF shield of the preclinical MRI system. To avoid inhomogeneity of RF magnetic field occurring in the close proximity of periodic structure, the RF coil is located 2–3 mm away from the region of interest.

Each RF source is defined in a model as a lumped port with the impedance of 50 Ω. Impedance of RF coil inputs were matched to the impedance of ports at resonance frequencies using matching circuits consisting of L=70 nH inductor and C=1-20 pF variable capacitors connected according schematic in Fig. 2.

Fig. 3 shows the calculated frequency dependence of reflection and transmission coefficients for developed RF coil. According to this plots the RF coil is tuned and matched at the impedance of 50 Ω at two Larmor frequencies of 376 MHz (^{19}F) and 400 MHz (^{1}H). The transmission coefficient curves illustrate the decoupling of two ports at both Larmor frequencies.

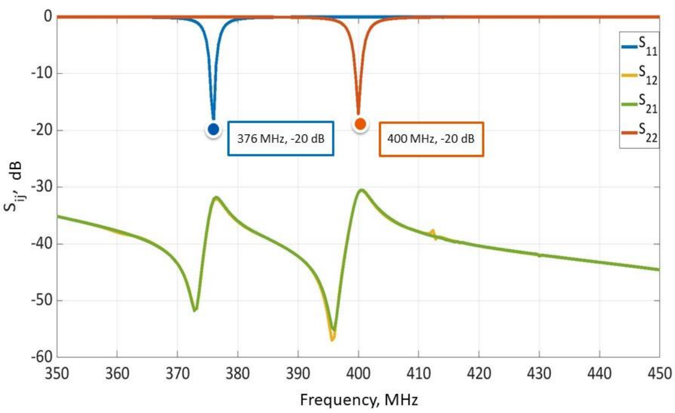

Fig. 3. Calculated frequency dependence of the reflection and transmission coefficients of the RF coil ports

Each eigenmode corresponds to a specific distribution of the RF magnetic field created by the RF coil. Calculated RF magnetic field maps of the coil at two Larmor frequencies are presented in Fig. 4. in the central cross-section of coil.

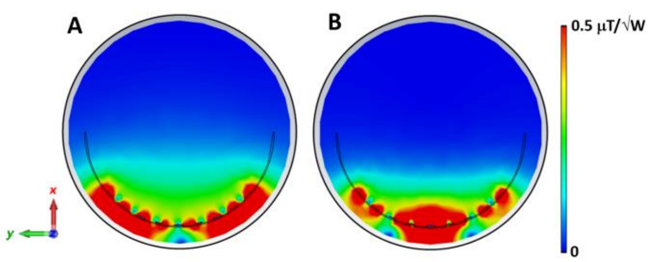

Fig. 4. Calculated magnetic field distributions in the central transverse cross-section of RF coil at 376 MHz (^{19}F) corresponding to the first eigenmode (A), at 400 MHz (^{1}H) corresponding to the second eigenmode (B)

Due to the obtain field maps it is seen that the RF is suitable for preclinical applications at two Larmor frequencies of 376 MHz (^{19}F) and 400 MHz (^{1}H) simultaneously.

IV. Conclusion

A transceiver RF coil for preclinical 9.4 T MRI of mouse lungs has been proposed. Operation of the coil is due to excitation of orthogonal eigenmodes in the RF coil at Larmor frequencies of ^{19}F and ^{1}H – 376 MHz and 400 MHz respectively to perform complex study of mouse lungs tissue fibrosis. The developed dual-tuned coil allows independent operation at two Larmor frequencies due to orthogonal eigenmodes excitation. Due to the obtained numerical results, the developed RF coil is suitable for small-animal preclinical applications at 9.4 T.

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